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Wind farm noise impact in France:
A proposition of acoustic model improvements
for predicting energy production

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Abstract

Despite all environmental and economic advantages of wind power, noise emission remains an issue for population acceptance. In France, the current noise emission regulation defines noise emergence level thresholds, leading to wind turbine curtailment. Great energy generation losses and thus lost revenues are at stake. This master thesis presents current acoustic campaigns conducted for the development of a wind power project in France and proposes acoustic model improvements to predict curtailment losses before the construction of the wind farm. It first gives insights about the French wind power context and a literature review of available technologies to reduce noise emission from the blades. It then presents the particularities of French regulation of emergence levels and the use of the norm NFS 31-114 during the commissioning acoustic control. It explains the current acoustic model used at the development stage to predict noise emission and curtailment and finally proposes improvements such as considering the topography, the environmental characteristics and the use of uncertainties.
Summary

Context

Amongst all impact assessments conducted at the development phase, the acoustic one is probably the most sensitive in the realization of the business plan. Looking at current performances of French wind farms from ABO Wind, three wind farms over seventeen have acoustic curtailment, representing 26 wind turbines over 155 installed in total. Financially, it represents 624k€ of loss per year, or 12 millions of euro on a life time of 20 years. It shows that acoustic performance is one of the key for a viable project. It is then essential to get reliable acoustic estimations at the development phase in order to keep a great selling project value while being confident to respect the acoustic legislation at commissioning time.

This summary reminds some basic acoustic principles and the existing technologies reducing the noise from wind turbines. It presents the problematic, the current acoustic assessment methods defined by the norm 31-114. From this, current methods and hypothesis used during the acoustic model at the development phase are described. Finally, some model improvements are proposed. With a better model, it is expected to get results closer to reality which will most of the time also correspond to greater project values.

Acoustic basics, noise origin and literature review of existing technologies

a. Acoustics basics

One has to make the difference between sound power and sound level. The sound power is the acoustic power that a source can deliver, expressed in Watts (example: speaker characteristic). The sound level is the « quantity » of sound (pressure difference) measured at one point, expressed in decibels (dB). The decibel A is a unit corrected by a coefficient in order to represent the human ear sensitivity (more sensitive to high frequency noises). Sound levels cannot be simply added, they use logarithms. Thus, the sum of two identical sound levels will only give an increase of 3dB (35dB+35dB=38dB and not 70dB). With the same principle, a weak sound level will not be significant compared to a higher sound level (30dB+45dB≈45dB).

a. Noise origin

Noise from wind turbines comes from two sources: the mechanical and the aerodynamical noise. The mechanical noise comes from the generator, the cooling system amongst others and can be decreased easily using good acoustic insulation materials; the noise is usually not perceptible at 500m (minimum distance of households from wind turbines). The aerodynamic noise from the blades is the strongest noise. It comes from turbulences created around the rotating blade and the pressure difference is proportional to the rotation speed at the power 5 (curtailing the rotation speed is therefore a good solution as described later). The two figures below show the different type of turbulences and their localisation on the blade (colours on the right figure).
The propagation of the sound depends on different parameters such as the wind direction, the temperature gradient, the acoustic absorption of the terrain. Technologies have been designed to reduce turbulences and thus the noise emitted. Numerical simulations allow designing blades with better acoustic performances without reducing the power production. Serrated trailing edge can also reduce the noise emission by few decibels. Clean blades improve the aerodynamic and thus acoustic performances as well. Otherwise, active controls are used such as acoustic curtailment. Weather data and curtailment plan determined during the development phase are used in a feedback loop to control the rotation speed of the blades. The diagram below illustrates the principle of acoustic curtailment.

![Diagram of acoustic curtailment](image)

**Figure S.1** Aerodynamic sources of noise from a wind turbine blade

**Figure S.2** Noise origin on a wind turbine

**Figure S.3** Overall acoustic curtailment block diagram
Problematic and current acoustic assessment methods

a. Commissioning method using the norm 31-114

Since the text of the 26 August 2011, wind turbines are part of the so-called ICPE (Installations Classified for the Protection of the Environment in French). Acoustic assessment studies have then to follow the version v3 (July 2011) of the norm project NFS 31-114 when commissioning the wind farm and controlling the noise level. A working group is in charge of writing the final version. Before this last version is published, the most recent version created by this group (version v9, February 2013) has been used in this report. A separated text should also be published in the law to define the way of interpreting uncertainties. Anticipating these publications, the method expected to be validated soon is described below.

In a first step, microphones are placed at household locations surrounding the wind turbines. Once the wind farm is installed, existing noise measurement (without wind turbines running) and ambient noise measurement (with wind turbines active) are conducted. Leading these two measurements alternating short periods of time allows keeping roughly the same weather conditions. The wind is measured in the same time using anemometers at the top of wind turbines (or from a wind measurement mast) and then standardized with the method described on the figure below. It has been shown that direct measurements using a wind measurement mast of 10m high only are rarely reliable.

![Principle of standardized wind speed calculation](image)

**Figure S.4 Principle of standardized wind speed calculation**

Depending on the location conditions, homogeneous classes are defined (day/night, wind direction, season...). Pairs (10min average wind speed ; 10min median sound level) are plot on a graph and scatter diagrams are created for each homogeneous class. For each wind speed bin, the pair (wind speed bin average; median of sound level bin medians) is interpolated to the corresponding integral value of wind bin (see section 5.1 for more details). From this data of existing noise and ambient noise, emergences are calculated for each wind speed bin and each homogeneous class. Acoustic curtailment is finally determined in order to respect noise emergence regulation of maximum 3dB during the night and 5dB during the day. Uncertainties are calculated but their interpretation is not clear yet in the current version of the norm. A wind farm can be proven as being non-conforming but cannot be proven as conforming with a sufficiently high degree of confidence. This is due to uncertainties that are in the order of magnitude of the emergence values to respect.
a. Current acoustic assessment methods at the development phase

The period of measurement is so far defined only taking into account weather conditions (no rain) for representing the different acoustic specificities of the location. A proposition with other criteria of selection is described in the last part of this summary in order to get more representative results. Existing noise measurement and homogeneous classes definition is done the same way as defined previously. Acoustic contribution of wind turbines is modelled using software in order to estimate ambient noise and the emergences compared to the existing state. To do this, noise emission tables given by the supplier are used to simulate the noise source for each standardized wind speed bin. The way of using the supplier data can be improved and a more precise method is described in the next section. Different model parameters such as the wind direction influence and terrain specificities are defined by the acoustic consultant and should be looked deeper in future work in order to improve the reliability of the model. Finally, even if uncertainties will have to be calculated at the commissioning acoustic study, they are not used yet at the development phase. A proposition of method is described in the final section.

Model improvement propositions

a. Period of measurement choice

In order to anticipate the acoustic differences between seasons and estimate them precisely, it is proposed to increase the communication between the acoustic consultant and the environment one. An environmental pre-diagnostic would be realized every time in order to create a table showing the activity of the fauna and the type of flora existing along the year (leaves in the trees). Human activities such as road traffic and harvest time would also be taken into account. A table such as the one showed below could be done to characterize the loudest periods in the year at the specific location.

![Figure S. 5 Estimated acoustic ambiance from fauna and flora characteristics](image)

In order to represent the maximum and minimum values of existing noise on site, acoustic studies would be conducted at the corresponding loudest and quietest month. Moreover, in case of significant difference between summer and winter noise levels, this table would allow defining the two “acoustic seasons” according to these activities. Instead of the “administrative definition” of winter, seasons could be defined differently using the table in order to represent the acoustic seasons along the year. For example, a constraining curtailment defined on the winter period would have less impact on the energy production estimation if it can be demonstrated that it is necessary to apply it over 3 months instead of 6 months.
b. Topography influence in the standardization of the wind speed

When modelling noise emission from wind turbines for each wind speed bin, the wind speed is so far considered as being the same at all wind turbines, no matter the topography. However, for a same wind speed reference at the wind mast measurement, the wind speed at a wind turbine location 30m below for example would not be identical but lower. For this same wind speed reference at the wind mast, the noise emission value of the wind turbine will also be weaker than if the topography was not taken into account. In the standardization of the wind speed, it is then proposed to systematically take the topography into account so that the model and the simulation get closer to reality and thus closer to measurements that will be done at the commissioning time. Moreover, since wind measurement masts are usually installed on high locations, this would most of the time lead to more optimistic scenarios and thus to greater project value.

c. Uncertainties

If uncertainties are easy to calculate from the measurement data set at the commissioning time, it is on the other hand harder to estimate them at the development phase because of the model. Three main uncertainties can be taken into account: the existing noise measurement uncertainty (calculated as defined in the norm, from 0.5 to 3dB from previous acoustic reports), the uncertainty of the supplier on the noise emission value from its wind turbine (taken as 1dB from specifications), simulation uncertainty from the acoustic consultant (from 2 to 5dB). A sensitivity analysis was made, showing that the uncertainty of the simulated noise was the most sensitive on the final uncertainty, mostly when wind turbine noise emission is greater than the existing noise. In order to use these uncertainties and justify their use, a maximum emergence uncertainty value needs to be defined. Given the norm proposes a maximum value of uncertainty (noted S) for validating the measures at the commissioning control, it is proposed to use the maximum value defined by: \( U_{dev} = \min(U_{Eme}, E, S) \). \( U_{Eme} \) represents the emergence uncertainty value calculated at the development phase with the method proposed in this report (see section 6.3). \( E \) is the emergence value itself. \( S \) is the maximum uncertainty value defined by the norm (3dB in the current norm proposal but can change in the final version). In the development phase studies, emergences would then be showed subtracting the uncertainty value. This can be justified by the use of uncertainties in the future acoustic controls when commissioning the wind farm. Using this method, it is expected that results get closer to the future commissioning control results and in the same time show a greater project value.

Conclusion

Several solutions were proposed and can already lead to results more in accordance with the last version of the norm 31-114. It is expected that results become more reliable, while showing greater project values. According the financial department of ABO Wind, it is preferable to have an optimistic scenario and give the money back to the investor after commissioning if needed than decreasing the value of the project before selling it. Taking into account people living around the wind turbines, it will be better accepted and seen to increase the curtailment along the time if needed than decreasing it.

This work should be continued and particular attention should be paid to exact parameters used in the acoustic simulation from the acoustic consultant (however not always accessible). The way of presenting the results to the administration and to the investor should be also be précised. Other questions such as accumulation of wind farms and annoyance from amplitude modulation should be studied. Does an installed wind farm part of the existing noise of the field or not? Should it be taken into account in the acoustic studies of an extension project for example? The law and norms are still not clear on this point. The difference between developers in France and anywhere else will depend on their capacity to anticipate these regulation changes.
List of figures

Figure S. 1 Aerodynamic sources of noise from a wind turbine blade ........................................ iv
Figure S. 2 Noise origin on a wind turbine ................................................................. iv
Figure S. 3 Overall acoustic curtailment block diagram .................................................. iv
Figure S. 4 Principle of standardized wind speed calculation ........................................... v
Figure S. 5 Estimated acoustic ambiance from fauna and flora characteristics ................. vi

Figure 1 Proportion of wind power in renewable electricity production 2
Figure 2 Average power and size of installed wind turbines. Number of people supplied with electricity (with electrical heating) [4] .................................................................................. 3
Figure 3 Wind farm implantations of ABO Wind .................................................................. 4
Figure 4 Organizational map showing the tasks in each office over the world [from ABO Wind] ................................................................. 5
Figure 5 Prospection map with zones at 500m from houses and some constraints ............. 6
Figure 6 Construction platform seen at hub height [picture from ABO Wind] ...................... 7
Figure 7 Wind power project steps ..................................................................................... 7
Figure 8 Aerodynamic sources of noise from a wind turbine blade ...................................... 8
Figure 9 Noise origin on a wind turbine ............................................................................. 9
Figure 10 Noise level from different sources and comparison with a wind turbine 500m away [from ABO Wind] ................................................................................................. 10

Figure 11 Influence of the wind direction on sound propagation [10] .................................. 11
Figure 12 Wind profile upwind and downwind of a forest [13] ............................................. 11
Figure 13 Refraction of sound with (a) positive temperature gradient and (b) negative temperature gradient [12] ................................................................. 11
Figure 14 Amplitude modulation and frequency modulation [14] ....................................... 12
Figure 15 Relative response of human ear according to the chose dB scale (A, B or C) ........ 13
Figure 16 Operator removing trips from serrated blade ..................................................... 17
Figure 17 Performance comparison between clean, untreated and tripped blade [9] .......... 18
Figure 18 Noise reduction for 1 and 5% power loss [27] ..................................................... 19
Figure 19 Power reduction for fixed noise levels [27] ........................................................ 19
Figure 20 Rotational speed setting for the different noise level scenarios [27] .................... 19
Figure 21 Pitch setting for the different noise level scenarios [27] ....................................... 19
Figure 22 Functioning of a wind turbine [29] ................................................................. 20
Figure 23 Doubly fed induction generator power control [30] .......................................... 21
Figure 24 Rotor speed control block diagram ................................................................. 21
Figure 25 Overall acoustic curtailment block diagram ..................................................... 22
Figure 26 Power curve of a wind turbine of 2.7MW with several noise reduction modes (information taken from a supplier of ABO Wind, name of the turbine not communicated) ......................... 23
Figure 27 Power curve of a wind turbine of 2MW with several noise reduction modes ......... 23
Figure 28 Microphone and wind mast location ................................................................. 25
Figure 29 Principle of standardized wind speed calculation [reproduced from the norm 31-114] .................................................................................................................. 26
Figure 30 Existing noise scatter diagram according to wind speed for one microphone location and one homogeneous class .................................................................................. 27
Figure 31 Example of interpolation using the previous value for the wind category 5m/s ....... 27
Figure 32 Noise emission specifications given by the supplier for the turbine used in the project of Mayenne ................................................................. 33
Figure 33 Emergence noise levels (“E” column) for the homogeneous class 4 and curtailment plan for the same homogeneous class ................................................................. 35
Figure 34 Estimated acoustic ambiance from fauna and flora characteristics ......................................................... 37
Figure 35 Difference distribution between the two methods of calculating roughness length .......................... 39
Figure 36 Differences (in dB(A)) between the regression and the norm methods ................................................. 40
Figure 37 Link between the regression line and the calculation differences ............................................................ 41
Figure 38 Elevation impact on the wind speed reference ..................................................................................... 42
Figure 39 Standardized wind speeds (at 10m) and at the reference hub height .................................................. 43
Figure 40 Results taking the topography into account ......................................................................................... 44
Figure 41 Measurement validation for the commissioning acoustic campaign ..................................................... 46
Figure 42 Uncertainty use in the process of emergence noise calculation at the development phase 47
Figure 43 Impact of existing noise uncertainty on the minimum emergence noise for given existing and turbine noise levels of 35dB .................................................................................................................................................. 49
Figure 44 Impact of existing noise uncertainty on the minimum emergence noise for given existing and turbine noise levels of respectively 30dB and 40dB ................................................................................................................................. 49

List of tables

Table 1 Evolution of wind power in France from 2000 until 2011 [4] ................................................................. 3
Table 2 Estimation losses on French ABO Wind projects ................................................................................... 13
Table 3 Default values of type B uncertainties for ambient noise level measurements .................................... 29
Table 4 Default values of type B uncertainties for emergence noise level ....................................................... 30
Table 5 Potential benefit from proposed solutions ......................................................................................... 51
Table 6 Calculation of energy production per mode and wind speed ............................................................. 57
Table 7 Equivalent wind speed bins between v10m and v100m (last column) .................................................. 57
Table 8 Example of curtailment table defined by the acoustic consultant ....................................................... 58
Content

Acknowledgement ........................................................................................................................................... i
Abstract .......................................................................................................................................................... ii
Summary ........................................................................................................................................................ iii
List of figures .................................................................................................................................................... viii
List of tables .................................................................................................................................................... ix
Introduction ...................................................................................................................................................... 1
1. Context ......................................................................................................................................................... 2
  1.1. Wind power in France .......................................................................................................................... 2
  1.2. Presentation of ABO Wind .................................................................................................................. 4
  1.3. Wind power project steps .................................................................................................................... 5
2. Acoustic review ........................................................................................................................................... 8
  2.1. Origin of the noise ............................................................................................................................... 8
  2.2. Impacting parameters and sound propagation .................................................................................. 9
  2.3. Impacts on human health .................................................................................................................... 12
  2.4. Vocabulary and measurement units ................................................................................................. 12
3. Noise problematic faced by wind power developers .............................................................................. 13
  3.1. Impact on production due to acoustic curtailment ............................................................................ 13
  3.2. French noise regulation ..................................................................................................................... 14
  3.3. Current acoustic campaigns and their impact on the project ........................................................... 15
  3.4. Problematic ......................................................................................................................................... 15
4. Literature review ....................................................................................................................................... 16
  4.1. Technology review ............................................................................................................................. 16
    4.1.1. Optimizing the overall airfoil design ............................................................................................ 16
    4.1.2. Reducing the airfoil tailing edge noise ...................................................................................... 17
    4.1.3. Curtailment without significant power losses ......................................................................... 18
    4.1.4. Curtailment inducing power losses .......................................................................................... 20
5. Description of the current process of measurement ............................................................................. 24
  5.1. Norm for the commissioning control ................................................................................................. 24
    5.1.1. Definition of terms and parameters ............................................................................................ 24
    5.1.2. Noise and wind measurement .................................................................................................... 25
    5.1.3. Calculation of standardized wind speed .................................................................................... 26
    5.1.4. Calculation and representation of existing noise ....................................................................... 27
Introduction

Wind power is a proven renewable technology becoming more and more competitive and increasing its share in the global energy mix in the world and in France. Despite all its advantages, noise emission is still an issue regarding the comfort of people living around wind turbines. To reduce this impact, France adopted a regulation using the concept of emergence noise level. Compared to the existing noise, new installed wind turbines should not imply a noise level increase of more than 5 dB(A) during the day and 3 dB(A) during the night. This regulation can result in wind power curtailment and million euros of production losses for the developer and operator.

However, the norm NF S 31-114 defining how to assess the noise impact once the wind farm is built is under development and some parts such as the method to calculate uncertainties and their interpretation is not set. Moreover, the way to predict noise emissions at the development phase has not been defined yet. This noise estimation at the development phase will nevertheless lead to the calculation of the business plan and define the selling value of the project. It is then essential to have a reliable acoustic model at the development phase, before the control with the norm 31-114 at commissioning. We can wonder if hypothesis of the norm should be taken into account at the development phase or if different criteria should be added in order to have a more reliable model. ABO Wind is an international company developing wind farm projects and interested in improving the acoustic model at the development phase in order to optimize energy production while respecting the legislation.

The first part will describe wind power development status in France, the company ABO Wind and the different steps for developing a wind power project in France. Noise origin and sound propagation will be explained in a second part. A literature review about existing technology and strategy to reduce noise emission from wind turbines will be presented in a third part. The fourth part analyzes French legislation and exposes in more details the challenge faced by wind power developers in France. The following section presents the process to lead acoustic campaigns using the norm when commissioning the wind farm and the current method and model used at the development stage. Finally, propositions to improve the reliability of the development phase acoustic model are detailed.
1. Context

1.1. Wind power in France

Even if wind power is increasing its share, France is known for having its main electricity production from nuclear energy. In 2012, it represented 75% of the total electricity generation. The share of renewables is growing up and reached 16% of electricity generation the same year. The remaining 9% is produced from coal, oil and gas \(^1\). Wind power represented 2.8% of electricity generation in France in 2012. Figure 1 shows the different sources of renewables and their share. Amongst renewables, wind power remains the main source of electricity developed in France with 60%. Feed-in tariffs allow any power generation operator to sell the electricity produced to the national electricity operator EDF. The contract lasts 15 years with a fixed price of 8.2cts of euro per kilowatt-hour for the 10 first years. Then, it follows the market price of electricity in between a fixed range in order to guarantee a minimum selling price. Market electricity price in France was around 6cts of euro per kWh in 2013 \(^2\). The additional cost of wind power energy is quite low and provided by national subsidies.

![Electricity generation proportion amongst renewable sources (without hydro power)](source: RTE \(^1\))

**Figure 1 Proportion of wind power in renewable electricity production**

Unlike Germany or Denmark, wind power developed only recently in France. The number of project greatly increased in the last years. Table 1 shows the evolution of projects and the number of equivalent people supplied with electricity from wind farms (with electrical heating taken into account). In 2013, it is 7821MW that are installed \(^3\). The French objective in the context of the 20-20-20 European goals for 2020 is to install 19 000MW onshore (and 6000MW offshore) \(^4\).
Table 1 Evolution of wind power in France from 2000 until 2011 [4]

<table>
<thead>
<tr>
<th>Year</th>
<th>Installed power yearly (MW)</th>
<th>Cumulated power (MW)</th>
<th>Energy produced (GWH)</th>
<th>Number of equivalent people supplied with electricity (with electrical heating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>40</td>
<td>61</td>
<td>70</td>
<td>29000</td>
</tr>
<tr>
<td>2001</td>
<td>31</td>
<td>92</td>
<td>131</td>
<td>54000</td>
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<tr>
<td>2002</td>
<td>52</td>
<td>144</td>
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<td>244</td>
<td>363</td>
<td>150000</td>
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<td>2004</td>
<td>146</td>
<td>390</td>
<td>577</td>
<td>237000</td>
</tr>
<tr>
<td>2005</td>
<td>367</td>
<td>757</td>
<td>963</td>
<td>395000</td>
</tr>
<tr>
<td>2006</td>
<td>810</td>
<td>1567</td>
<td>2169</td>
<td>890000</td>
</tr>
<tr>
<td>2007</td>
<td>928</td>
<td>2496</td>
<td>4140</td>
<td>1725000</td>
</tr>
<tr>
<td>2008</td>
<td>1081</td>
<td>3577</td>
<td>5653</td>
<td>2500000</td>
</tr>
<tr>
<td>2009</td>
<td>1136</td>
<td>4713</td>
<td>7800</td>
<td>3250000</td>
</tr>
<tr>
<td>2010</td>
<td>1253</td>
<td>5966</td>
<td>9600</td>
<td>4000000</td>
</tr>
<tr>
<td>2011</td>
<td>825</td>
<td>6792</td>
<td>11900</td>
<td>5000000</td>
</tr>
</tbody>
</table>

The technology has also improved. Wind turbines are becoming higher, larger, with an overall greater power. Figure 2 shows the evolution of the type of turbines installed in France since 2000. Less wind turbines are today built for the same wind farm power. However, building higher wind turbines leads to restrictions regarding military and civil aviation.

![Power and average size of installed wind turbines](image)

**Figure 2 Average power and size of installed wind turbines. Number of people supplied with electricity (with electrical heating)** [4]
Wind power is given a great importance in Europe and particularly in France to lead the energy transition. However, the development is controlled and regulated with laws and norms which are different in each country. This report is focusing on French legislation. In France, the most restricting rule is the minimum distance to households. Wind turbines cannot be installed at less than 500m from any household. When households are scattered, available zones to install wind turbines are limited. Additionally, wind turbines have to be kept away from radars and air military training zones. These zones can also be impacted by an environmental protection zone or an historical conservation zone. Specific authorizations and studies have then to be performed to be allowed to install wind turbines in these locations.

1.2. Presentation of ABO Wind

To reach the European goals in 2020, the government gives wind power objectives for each region of France. Private companies are then in charge of finding the locations and lead the projects. In France, around 50 different companies work on the development of wind power projects. ABO Wind is one of them. It is an international group founded in 1996 in Germany by Jochen Ahn and Matthias Bockholt (who gave their initials to the name of the company). 280 people are nowadays working around the world and 450 wind turbines representing 860MW of capacity have been installed. The group has been working in France since 2002 with 40 employees currently working in Toulouse, Orléans and Nantes. ABO Wind in France has achieved 220MW of installed capacity and represented 10% of the new wind power installed capacity in 2013.

ABO Wind leads the prospection to find new site locations, manages the contact with locals, organizes the business and technical planning, arranges international bank financing and delivers turnkey wind farms. Once constructed and commissioned, ABO Wind takes on the commercial and technical management of wind farms. It now manages 250 wind farms. During the development and the financing of projects, ABO Wind always encourages locals to invest in the project in order to have local beneficial effects. Figure 3 shows the implantation of ABO Wind wind farms in Europe. Figure 4 shows the international implantation of ABO Wind.
ABO Wind is mainly present in Europe and particularly in France and Germany. If wind power is already well developed in Germany, French objectives are still far from being reached. Some wind farms are also running in Ireland, Spain, Bulgaria and newly Finland. The technical department calculating energy production and analyzing wind data and the financial department are situated in Germany.

1.3. Wind power project steps

A wind power project needs around 6 or 7 years from the first contact with the town mayor to the first blade rotation producing electricity. The project can be divided in 5 different steps: Prospecting, planning, financing, construction and operation.

Prospecting consists in finding new available zones where wind turbines could eventually be built. As illustrated on figure 5, the software MapInfo is used in order to display on the same map all the constraints: zones at 500m from houses, environmental zones, radars, military zones, connection points to the grid. From this map, suitable zones are identified. Mayors are then phone called in order to get an appointment with them and present wind power and a potential project of wind farm on their municipality. After a first contact with the mayor, land owners of the potential zone are contacted and the project is presented. With their agreement, a commitment to lease is signed between the land owner and ABO Wind. Once the municipality has given its agreement and enough commitments to lease have been signed, the project then enters in the planning phase.
The planning phase consists in conducting the different impact assessment studies for realizing an application for a building permit. Four studies are done. The wind energy study evaluates the wind potential by installing a wind measurement mast on the field. Energy production is then estimated with these measurements and power curves from wind turbine suppliers. It is thus an essential study for the company and investors since it will determine the revenues of the project. The second study assesses the environmental impacts on the fauna and flora around the considered zone. Impacts on birds and bats are particularly studied as well as migration paths. The third study is a landscape study. Photomontages are realized in order to assess the impact of wind turbines installation on the landscapes. Winds turbines should not be too visible from nearby houses and particularly from historical monuments that are numerous in France. The last study consists in realizing an acoustic impact assessment. It determines which households would be impacted and by which noise level. According to the results, curtailment of wind turbines will then be estimated and considered in the estimation of the energy yield. Once these four studies are done and validated, the application of building permit and operation license are submitted. A public survey is conducted in the meantime and the decision from the prefect is given one year after the complete submission.

Financing of the wind farm is realized by private investors. ABO Wind encourages people living near the turbines to invest in the project. It improves local acceptance and financial revenues for the region. The rest is funding by external investors whose ABO Invest which is a subsidiary company from ABO Wind.

Figure 5 Prospection map with zones at 500m from houses and some constraints
Once all authorizations are obtained and financing is set, the construction can start. Accesses for trucks bringing the equipment were determined and found previously. The foundation in concrete is first completed. Towers are then raised up and blades finally fixed to the hub. Figure 6 shows the construction platform from the hub of the wind turbine.

The last phase is the operation that will last between 20 and 30 years. Figure 7 shows the different steps of a project and the timeframe for each of them.

Given this context, noise impact assessment is only a part of the whole project. It is however essential to estimate energy production and the value of the project. It will determine the viability of the project. Before describing the noise impact assessment itself, the origin of the noise from wind turbines, its propagation and impacts on humans are presented.
2. Acoustic review

2.1. Origin of the noise

Noise from wind turbines is emitted from two main origins. Noise can have a mechanical source or aerodynamic source. Noise from a mechanical source is due to the movement and the functioning of the mechanical elements inside the nacelle. The gearbox and the main shaft are emitting some noise while rotating and vibrating. The generator itself and the pumps used for the cooling system also produce noise. The level of this noise is not high and can be reduced using low noise emission equipment and adding sound insulation. Even this can be a large part of the noise emitted, it is in modern technologies dominated by aerodynamic noise [5].

Noise from aerodynamic source is caused by the wind passing through the rotor surface and the turbulences around the rotating blades. Three different categories of noise are distinguished: low frequency noise, inflow turbulence noise and airfoil self-noise. The low frequency noise is due to the blade passing in front of the tower and has an impact which is not significant [6]. The inflow turbulence noise is due to the external airflow impacting the leading edge of the blade. Finally, the airfoil self-noise emission corresponds to the noise emitted by the blade itself. This last category can be divided in 5 sub-origins of noise: the turbulent and the laminar boundary layers trailing edge noise, the laminar/turbulent transition noise (or stall noise), the trailing edge bluntness noise and the blade tip vortex formation noise. These different origins are shown on figure 8 [7].

![Figure 8 Aerodynamic sources of noise from a wind turbine blade](image)

Boundary layers on a wind turbine blade are successively laminar and then turbulent. A part of the airflow is obviously laminar in order to avoid stall and make the blade rotate using the lift force, like a plane. Depending on the angle of attack and the shape of the blade, the airflow then becomes turbulent. The transition between these two states emits noise and the turbulent boundary layer itself also produces noise. At the edge, eddies (or wake effect) are generated because of the edge bluntness. These eddies are also participating to the drag force. Finally the tip itself also generates turbulences, creating more noise. These different noise sources are more deeply described and discussed in the paper of Brooks et al. [8]. Acoustic measurements show that the highest sound level is not coming from the very tip of the blade but slightly before, as shown on figure 9 [9].
Turbulences depend on the blade profile, on the tip shape and the condition of the blade surface. A study conducted by Olivier Fegeant showed that the noise level emission increases with the rotation speed of the blade at the power five \(^5\). Sound emitted from the wind turbine generates greater noise with longer blades and higher tip speed. Noise level is the factor taken into account in the French sound emission legislation but it is not the only parameter affecting people discomfort. The frequency of the noise and the modulation of amplitude are two parameters that can potentially cause discomfort as well.

2.2. Impacting parameters and sound propagation

The sound is a mechanical wave due to a pressure difference. The pressure can be expressed as an atmospheric pressure added with an acoustic pressure.

\[
P_{\text{tot}} = P_{\text{atm}} + p
\]

(Equation 1)

\(p\) is then measured in Pascal by a sonometer. The sound is qualified by its intensity and linked to the pressure as followed:

\[
I = \frac{p^2}{\rho_0 c} \quad \text{(in W/m}^2\text{)} = \frac{p^2}{400}
\]

(Equation 2)

With \(\rho_0\) the air density (about 1.2kg/m\(^3\)) and \(c\) the sound velocity (about 340m/s). It also corresponds to the power of the sound per unit area and can be expressed as:

\[
I = \frac{W}{S} = \frac{W}{4\pi r^2} \quad \text{(for a punctual source such as a wind turbine)}
\]

(Equation 3)

With \(W\) the acoustic power of the source and \(S\) the surface. The sound level is usually measured in decibel, using an intensity reference value \(I_0=10^{-12}\) W/m\(^2\). It is given by:

\[
L = 10 \log \left( \frac{I}{I_0} \right)
\]

(Equation 4)
The sound level \( L \) decreases with distance since the sound energy is distributed in a larger area, it is defined as the geometric dispersion effect. It is here shown that doubling the distance leads to a reduction of 6dB. Let’s consider \( R=2r \), then:

\[
I_R = \frac{W}{4\pi R^2} = \frac{W}{4\pi (2r)^2} = \frac{I_r}{4}
\]

(Equation 5)

And \( L_R = 10\log \left( \frac{I_R}{I_o} \right) = 10\log \left( \frac{I_r}{I_o} \right) = 10\log \left( \frac{r}{r_0} \right) - 10\log 4 = L_r - 6dB \)  

(Equation 6)

In case of different sources, the sound levels in decibel are not added to each other because of the log. Considering two sound levels \( L_1 \) and \( L_2 \), the sum \( L_{tot} \) between these 2 sound levels will be calculated with:

\[
L_{tot} = 10\log \left( 10^{L_1/10} + 10^{L_2/10} \right)
\]

(Equation 7)

Taking the example of two exact same sound levels \( L_1 = L_2 \), then we get:

\[
L_{tot} = 10\log \left( 2 \times 10^{L_1/10} \right) = 10\log 2 + L_1 = L_1 + 3dB
\]

(Equation 8)

It means that doubling the sound level at one point is equivalent to increasing it by 3dB. Finally, the so-called masking effect is a property of the sound showing that if there are big differences of value between two sound levels, only the louder will count. For example, if a sound level \( L_1 \) is about 25dB and another source \( L_2 \) is about 40dB then the total sound level will remain at the highest value of 40dB. The contribution of \( L_1 \) will be masked by the second one. These results are not always instinctive. When considering the noise coming from different sources, calculation has to be done properly to really estimate the final value. In order to get an idea of the noise emitted by a wind turbine compared to other sources, figure 10 gives a scale with noise references.

Figure 10 Noise level from different sources and comparison with a wind turbine 500m away [from ABO Wind]
Propagation of the sound depends on several environmental parameters, leading to more or less annoyance for people. Differences of propagation are due to the wind direction, to reflection and to meteorological criteria such as the wind speed gradient and temperature gradient. Wind direction changes the way of propagating the sound and can create shadow areas depending on the wind gradient as shown on figure 11. Distance is not the only factor to take into account when measuring the impact of a noise source on houses.

![Figure 11 Influence of the wind direction on sound propagation](image)

The wind profile depends mainly on the roughness of the terrain. On a flat terrain without obstacles, the surface roughness will be low, leading to small wind speed gradient. For the same potential, the wind speed will be stronger at low altitudes. A terrain with trees, buildings and hills will have a higher surface roughness, leading to a greater wind gradient. Figure 12 shows a weaker wind gradient upwind than downwind of a forest. Terrains without obstacles will obviously propagate the sound further and louder.

![Figure 12 Wind profile upwind and downwind of a forest](image)

Temperature gradient also influences the propagation of the sound. Temperature varies with heights depending on weather conditions. Depending on the gradient – being positive or negative – the sound will propagate in a different way. Figure 13 shows the two cases of propagation with a positive and negative temperature gradient. This difference is usually observed between day and night time. During the night, the ground has a thermal inertia, being warmer than the air and thus creating negative gradient. During the day, the air is warmer than the ground, creating a positive gradient.

![Figure 13 Refraction of sound with (a) positive temperature gradient and (b) negative temperature gradient](image)
2.3. Impacts on human health

If too high, sound produced by wind turbines can affect people living in houses nearby the wind farm. The sound induced by wind turbines is a humming noise that people generally assimilates to a “sort of mosquito buzzing”. If too loud, the wind turbines can cause an auditory fatigue leading to a physical fatigue and annoyance. During the night, abnormal elevated noise from wind turbines can also cause sleep disruption as an automotive highway would do. However, according to a study conducted by an independent expert panel, it has not been proven that annoyance from this noise was not correlated to the acceptance of the project. It can be easily understood that people supporting the project would stand the noise annoyance better than people rejecting it \[13\].

If regulations are usually only taking sound level into account, the frequency of the sound and the amplitude modulation can also cause annoyance. Amplitude modulation and frequency modulation phenomenon which are actually used to diffuse information are illustrated on figure 14.

![Figure 14 Amplitude modulation and frequency modulation][14]

Amplitude modulation noise from wind turbines is usually described as a swishing noise due to the blade passing in front of the mast \[11\]. This periodic phenomenon causes an amplitude modulation in the sound propagating to the houses at a frequency linked to the rotation speed of the blades. Annoyance increases with this amplitude modulation as shown by an Australian study in 2009 \[15\].

Infrasound is usually pointed as being a human health issue. Infrasound refers to vibrations having a frequency below 20Hz. It has been proven that infrasound cannot be heard by human ear if their amplitude is below 100dB (that corresponds to an explosion sound level). An international study conducted by an independent expert panel and a study conducted by the French academy of medicine show that infrasound does not have any negative impact on human health \[16\] \[17\].

2.4. Vocabulary and measurement units

Sound amplitude is measured using decibel units. Two different types exist: decibel SPL (Sound Pressure Level) and decibel A which is balanced by a factor defined in the international norm IEC 61672-1. Two noises of the same amplitude will be felt differently from the human ear according to the frequency. Particularly, the human ear is more sensitive to high frequency sounds. Decibel A takes into account the human hearing sensitivity to the frequency and is noted dB(A). Figure 15 shows the difference of relative response of human ear according the chosen scale \[18\]. Giving this, one has to know that three different categories of sound are distinguished by the French law. The existing sound corresponds to the sound present in the field before any installation of wind turbines. The emission noise is the sound coming from the only source of wind turbines without considering the environment. The ambient noise is the sum of the existing noise and the emission noise from wind turbines.
3. Noise problematic faced by wind power developers

3.1. Impact on production due to acoustic curtailment

All the projects do not necessarily need curtailment in order to respect the acoustic regulation. After conducting a survey about all wind farms developed by ABO Wind and currently running in France, results show that three wind farms out of 17 need curtailment due to acoustic issues. It represents 26 turbines over 115. The calculation method to estimate energy losses from the acoustic curtailment plan is described in Annex. Table 2 shows the calculated energy and financial losses.

<table>
<thead>
<tr>
<th>Loss estimations</th>
<th>Energy loss percentage</th>
<th>Energy loss (MWh/a)</th>
<th>Financial loss (in €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project 1</td>
<td>8,65%</td>
<td>3633</td>
<td>297 906,00 €</td>
</tr>
<tr>
<td>Project 2</td>
<td>6%</td>
<td>2619</td>
<td>214 758,00 €</td>
</tr>
<tr>
<td>Project 3</td>
<td>2,58%</td>
<td>1355</td>
<td>111 110,00 €</td>
</tr>
<tr>
<td>14 other projects</td>
<td>0%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Average loss per year</td>
<td>1,01%</td>
<td>447</td>
<td>36 692,59 €</td>
</tr>
<tr>
<td>Total loss per year</td>
<td>/</td>
<td>7606</td>
<td>623 774,00 €</td>
</tr>
<tr>
<td>Average loss on 20 years</td>
<td>1,01%</td>
<td>8949</td>
<td>733 851,76 €</td>
</tr>
<tr>
<td>Total loss on 20 years</td>
<td>/</td>
<td>152133</td>
<td>12 475 480,00 €</td>
</tr>
</tbody>
</table>

It can be seen that losses can go up to 8% because of household’s configuration around the wind farm. On average, it represents 1% of the production from ABO Wind in France. The price taken into account is the feed-tariff of 8.2cts of euro. It is then an average of 37k€ that is lost every year per project and an actual sum of more than 600k€ per year. Considering a life time of 20 years, it then goes up to 700k€ of financial losses per project on average and a total loss of more than 12 million of euro. This is clearly showing the great importance of acoustic studies in the development of wind farms.

Figure 15 Relative response of human ear according to the chose dB scale (A, B or C)
If these statistics concern wind farms that are currently running, equivalent acoustic loss estimation is done for projects under development as well. As it will be explained in section 5, an acoustic campaign is done at the development phase, leading to a curtailment plan which is used to calculate energy losses with the same method described in Annex. It leads to the definition of a business plan with a project value that can greatly change according to the acoustic losses defined previously. According to these losses, it can even be decided to not invest in a project because of lower project value.

### 3.2. French noise regulation

In some European countries such as Sweden, Denmark and Germany, only a maximum sound level has to be respected. For example in Sweden, maximum allowed noise emission from wind turbines outside dwellings is 40dB(A) and can be slightly lower for sensitive areas. It is 45dB(A) (40dB(A) for sensitive areas) in Denmark and different maximum values are used in Germany according to the type of building in the vicinity of the wind farm. France uses emergence limitations defined by the difference between the existing noise and the ambient noise with the wind turbines.

French law regarding noise regulation is set by the ministry of ecology, sustainable development, transports and housing and the last statutory order was signed and published the 26 august 2011. It can be found on [32](in French).

The law defines a maximum value of noise emergence that cannot be exceeded, compared to the existing noise before installation of the wind farm. Two categories, day – from 7am to 10pm - and night – from 10pm to 7am - are distinguished and show different emergence values. During the day, no more than 5dB(A) above the existing noise level is accepted. During the night, no more than 3 dB(A) above the existing noise level is accepted. If the ambient (or immission) sound - including the sound of wind turbines – does not exceed 35dB(A) at any time, no restrictions are applied.

Let us take an example to illustrate this. A developer is planning to install wind turbines in a field where the existing noise (before installation) is about 33dB(A). The developer hires an acoustic engineer to measure the ambient noise (with turbines running) at houses situated around the wind farm. Two cases can then be distinguished:

- If the ambient noise does not exceed 35dB(A) at these measurements points, no restrictions apply.
- If the ambient noise exceeds 35dB(A), the ambient noise cannot be over $33+5=38$dB(A) during the day and $33+3=36$dB(A) during the night.

The sound frequency distribution should also be homogeneous and no spikes more than 5 or 10dB in between given frequencies should be observed. The law also sets a maximum ambient noise level value of 70dB(A) during the day and 60dB(A) during the night. This ambient noise level has to be kept under these limits at a distance of $R=1.2 \times (\text{hub height} + \text{blade length})$ around each turbine.

The law is not defining the way of measuring noise level and how calculating noise emergences. When conducting an acoustic campaign at the wind farm commissioning, measurements and calculations have to respect the project of norm NF31-114, published on July 2011. This norm has been started but not finished yet so its latest publication in July 2011 is the reference. If scientists agree on how to measure emergences and how to link it to wind measurements, they do not agree on the calculation and interpretation of uncertainties.
3.3. Current acoustic campaigns and their impact on the project

As described in section 1, four different studies are realized at the development phase before applying for a construction permit: for the wind resource, the landscape, the environment and the acoustic. The latest is the one we are interested in. This acoustic campaign is conducted in order to measure the existing noise, model the field and simulate the noise coming from the wind turbines that would be installed. It gives an estimation of emergences and using the law described before, leads to curtailment time estimations. These estimations are then taken into account to predict energy production and finally calculate a project value for the business plan. The whole wind farm will be sold to an investor at this calculated price. Therefore, having a high but reliable value is essential.

Once the wind farm is built, a compulsory acoustic campaign is conducted to measure existing and ambient noise and assess whether emergence limitations are respected with the curtailment plan defined at the development phase. This acoustic study at commissioning time has to follow every step and criteria defined in the project of norm 31-114. If emergence limitations are respected but the curtailment plan is shown as being too restrictive, curtailment can be reduced. The project value would then increase compared to the initial estimation and the investor would pay slightly more. If higher emergences than allowed are detected, the curtailment plan will become more restrictive. Value of the project will then decreased compared to the initial estimation and ABO Wind will give the money difference back to the investor.

We could then think that if the acoustic study conducted at the development phase is not reliable, it would not matter much since a compulsory acoustic campaign is done when commissioning the wind farm. However, the project is sold before building it. So the entire value of the project is defined using the acoustic study conducted at the development phase. It needs to be optimistic to get a high project value but also reliable in order to avoid giving back money when commissioning the project. The whole problematic is then to use a model as precise as possible at the development phase to get a project value high enough to be sold but reliable enough to avoid bad surprises once in operation.

The wind power developer will prefer being optimistic by slightly overestimated the project value in the development phase study, for several reasons. As described before, this acoustic prediction will lead to the project value so selling the project a good price is a priority. Then, the commissioning control will not take place right on the day when turbines are ready to run. It can be conducted almost one year after their first day of operation. If curtailment is too restrictive, energy production will be lost until doing the control. The last reason is that it will be easier to increase curtailment if unauthorized emergences are shown than justifying to reduce curtailment time. The law protects people living around so it will always be harder to reduce curtailment time and thus slightly increase noise emission than increasing curtailment (and thus decrease noise).

3.4. Problematic

The acoustic study at the development phase is necessary for handing a construction permit and to make a business plan. However, no method is imposed for conducting it. What is known is that another compulsory acoustic campaign will be conducted at commissioning the wind farm and that at this moment the norm 31-114 will have to be respected. This norm was written for conducting measurement and not realizing estimation or simulation at the development phase. We can then wonder if every hypothesis of the norm should be taken into account at the development phase or if different criteria should be added in order to have a more reliable model. The aim of this report is to define a more precise model for realizing acoustic studies at the development phase. The better model should result in a good project value to be sold and be reliable enough to avoid great curtailment changes after the commissioning acoustic study.
Improving the reliability of the model does not instinctively mean that results would become more favorable for ABO Wind. Improving the precision can lead to more protection for the people living around or on the contrary to less restrictive curtailment time. If acoustic predictions at the development phase were so far globally matching the results at the commissioning control with the current status of the norm, the final norm that will be published will change the method and needs to be taken into account. Given current estimations and the new version of the norm, it is expected that increasing the reliability of the model will lead to more favorable results for the developer. Section 6 presenting the solutions for a more reliable model will show that current hypotheses are pessimistic compared to reality.

4. Literature review

Different technologies and principles exist in order to reduce aerodynamic noise emission from wind turbines. The technologies presented here have proven their ability to reduce noise emission. Since these technologies are not always available and viable, power curtailment remains the most efficient solution as it is going to be exposed.

4.1. Technology review

4.1.1. Optimizing the overall airfoil design

Industries are trying to make the blade profile as aerodynamic as possible to limit turbulences and thus noise emission. Numerical simulations are mostly used to improve the blade geometry and thus reduce the noise emission while keeping the same production capacity. Most of recent studies are based on a semi-empirical model. Each noise source is calculated using equations defined in previous studies and all sources are combined to simulate the total noise emission. Previous measurement campaigns are used to verify and improve the model. It is an optimization problem with a defined objective function and constraints. Multi objective functions can be used in order to maximize energy production while minimizing noise emission as it is done in the optimization study conducted by Rodriguez [19]. By modifying the chord, twist and airfoil shape, results show an improvement up to 12.4% of annual energy production while keeping the noise level constant and a reduction of 7.6% of overall sound pressure level while keeping a constant energy production. Another study done by Fuglsang and Madsen includes the noise emission in the objective function [20]. It shows improvements up to -3dB while keeping the energy production constant. The tip speed is then reduced, solidity increased and the twist modified, leading to a more expensive blade. Since economic gains on acoustic are not easy to estimate, the same authors realized another study including the cost of production in the optimization itself [21]. Designing the overall shape of the blade is not sufficient and some researchers focus on reducing one of the main noise source which is the trailing edge noise.
4.1.2. Reducing the airfoil trailing edge noise

As described previously, trailing edge noise can have its origin from the laminar and turbulent flow boundary layer and from the bluntness of the edge generating vortex-shedding. For an incompressible flow (which is the case for wind turbines), the trailing edge noise is proportional to parameters described as followed \[22]:

\[
\langle p^2 \rangle \propto \frac{\rho_0 U^5 L \delta}{r^2 D}
\]

(Equation 9)

\( \langle p^2 \rangle \) corresponds to the sound pressure intensity at a distance \( r \) from the trailing edge. \( \rho_0 \) is the air density and \( c_0 \) the speed of sound. \( U \) represents the air velocity near the edge and \( L \) the length exposed to the flow (blade section). Finally \( \delta \) measures the boundary thickness at the edge and \( D \) is a directivity function, depending on the observation angle to the edge.

As mentioned before, we find the proportionality of the sound pressure with the wind speed at power five, leading to proportionality with the sound level of a factor 5 (applying the logarithm on equation 9). This shows again the great importance of the tip speed which is directly linked to the air velocity \( U \) in equation 9. If turbulences cannot be suppressed, they can at least be reduced in order to decrease noise emission. Different technologies are today developed to achieve this objective.

Trailing edge serration is one of these solutions and can reduce significantly the noise due to trailing edge turbulences. A study written by Oerlemans et al. shows improvements of -3.2dB of noise emission compared to the baseline scenario blade on a wind turbine of 2.3MW \[23\]. The principle of serration is illustrated on figure 16. Work achieved by M. Gruber et al. proposes a model to simulate the improvements resulting from the serrated edge. It can be concluded that flow mechanisms are still not fully understood at the serrated edge and other noise sources play a major role in the total noise emission from wind turbine blades. However, reduction of 3 to 5dB was confirmed experimentally \[24\]. A similar system is used on other blades, using trailing edge brushes. Finez et al. found that adding brushes to the edge of the blade can reduce noise emission by 3dB in the [600Hz – 2000Hz] frequency range \[25\].

In another study linked to the SIROCCO program, Schepers et al. compare the noise emission of a normal blade compared to a clean and a tripped one. Figure 17 shows the results on the study. It is clear that having a clean blade achieves better performances, for both energy production and noise reduction. An increase of 0.6dB compared to the normal blade is found due to tripping \[9\].
Finally, porous blades near the edge were shown as reducing the noise emission. Airfoils made of different homogeneous porous material were tested and compared with the non-porous material. As done in the previous cited studies, microphones were installed to experimentally measure the difference of noise emission. Geyer et al. showed that a reduction up to 10dB in the low and medium sound frequencies was possible using porous material \[26\].

Redesigning the blades costs money and is not always guaranteed to achieve viable acoustic reductions. If technology improvement is a major source of improvement in noise emission reduction, it is not always ready or viable to be industrialized. Companies installing wind turbines have only the choice between existing models proposed by suppliers. Since these new blades are not commercialized yet, other solutions have to be found. The current solution for existing wind farms is the use of curtailment, reducing the rotation speed and thus decreasing the noise emission. As seen before in the equation, it is by far the most efficient way of reducing aerodynamic noise.

4.1.3. Curtailment without significant power losses

Studies showed that changing the pitch angle and the tip speed can reduce noise emission without impacting energy production significantly. The study done by Fuglsang and Madsen and cited before \[20\] showed that noise emission can be reduced by optimizing the geometry of the blade but also by reducing the tip speed and adapting the pitch angle. Another study conducted by G. Leloudas et al. \[27\] compared simulations from a semi-empirical acoustic model and showed improvements by changing the tip speed and pitch setting. Using a noise minimization in their objective function, they showed that significant reduction of noise can be achieved while sacrificing only 1% of power. They compared the result with simulation sacrificing 5% of power. Results are shown on figure 18. Noise reduction reaches 2dB maximum for 1% power loss and more than 4dB sacrificing 5% of power. On the contrary, they also tried to maximize power for fixed noise levels. Results are presented on figure 19.
To obtain results for the different noise scenarios presented on figure 18 and 19, pitch angle and rotational speed have been modified as shown on figure 20 and 21. The pitch angle is increased and in the same time the rotational speed decreases, leading to a reduction of noise emission. A decrease of 4 rpm as shown on the graph represents a reduction of \( \frac{4 \text{rpm} \times 2 \pi}{60s} \times R_{\text{blade}} \) (in m/s). According to the specifications of the SWT-2.3-93 from Siemens \(^{[28]}\), the blade length is 45m and thus the reduction of speed at the tip is about 68km/hour, knowing that the maximum tip speed is about 271km/hour and the minimum about 102km/hour (respectively 16rpm and 6rpm given by the supplier).

These gains are not always sufficient to respect the noise emission limitations and thus more power needs to be curtailed. Wind turbine suppliers then integrate noise reduction modes in the power controller of the wind turbine in order to reduce the rotational speed and the noise emission. In order to understand the impact on the wind turbine output, the functioning and basic power control systems are described below.
4.1.4. Curtailment inducing power losses

The different elements composing a wind turbine are shown on figure 22 [29]. A yaw system enables the turbine to face the wind. The rotation of the rotor is transmitted to the generator with or without a gearbox. Four main types of power control are used: aerodynamic power converter (fixed speed turbines), the rotor-resistance converter, the doubly-fed induction generator and the full-converter. Fixed speed wind turbines use only blade pitching or stall control (active or not) to keep the rotational speed constant. The rotor-resistance type uses an additional resistance on the rotor which is electronically controlled. By controlling the slip (difference of speed rotation between the rotor and the magnetic field), it gives a control speed range of 2-5%. Doubly fed induction generators directly transmit 2/3 of the output power to the grid and the rest is controlled by a full electronic converter. It then allows a power control of up to 30% of both active and reactive power. The last type, the full scale converter, gives extra losses but enable to electronically control 100% of the power. Most of current generators are doubly-fed induction generators (DFIG) [30]. More details on power control of DFIG are presented on figure 23.

![Figure 22 Functioning of a wind turbine](image-url)
On figure 23, the need of power control comes from the wind availability and from the grid operator control system due to frequency stability needs (the consumption and production have to match). By modifying the pitch and the torque, the rotational speed is changed. The converter also modifies the active and reactive power transmitted to the grid according to its needs. The combination between rotor speed and generator control leads to adapted output power matching the requirements of the grid. In the case we are interested in, noise limitation is one more parameter added to the grid requirements and leading to pitch and torque changes and thus rotation changes.

Noise limitation implies reducing the rotational speed of the blades to reduce noise emission. Another power control system is put in place to reduce the rotational speed while keeping a torque adapted to maximize power output. A rotational speed is defined and the power controller intends to keep it constant by controlling both the pitch and the torque. Very different wind speeds can be measured, the rotor speed is usually the only measurement used in the feedback loops. Figure 24 is a diagram of the rotational speed control used for power control. 

Figure 23 Doubly fed induction generator power control

Figure 24 Rotor speed control block diagram
The instruction for the rotation speed is set using the acoustic studies realized when commissioning the wind farm. Conditions such as wind direction, season, time of the day will be defined and a noise reduction mode corresponding to a rotational speed will be decided. The way to define these conditions and classify them are described in section 5. What needs to be known here is that the instruction of rotational speed will come from the noise emission limitation that has to be respected in the given conditions. For example, if acoustic curtailment was decided for the wind speed bin of 5m/s every night in winter, adapted rotational speed will be used to respect this. A timer will detect the hour of the day and the season, an anemometer will measure the wind speed and transmit this information to the controller which will finally trigger the pitch motor (the actuator) to adapt the pitch angle and get the adapted rotation speed. A final diagram showing the global acoustic curtailment control is presented on figure 25.

**Figure 25 Overall acoustic curtailment block diagram**

If slowing down the rotor is not sufficient, turbines are finally stopped to avoid noise annoyance. However, one has to know that stopping a wind turbine has an impact much more important than only slowing it down. Figure 26 and 27 shows the power curve of two different models of wind turbines with curtailment modes. It can be observed that the power difference between the different modes can be high at high wind speeds, above 8-9m/s. Below this wind speed range, the differences are small and do not impact too much the energy production. These noise reduction modes are non-significant compared to stopping a machine. During the acoustic studies, we will always try to keep wind turbines running, even if they need to be slowed down. It will always give a higher energy yield.
As it has just been described, the best way for developers to reduce noise emission is to use acoustic curtailment and reduce the rotation speed of the rotor. It is then essential to define as precisely as possible the different conditions leading to the need of curtailment. The aim of this thesis is to model acoustic emissions as precisely as possible to get reliable estimates which are used as inputs in the acoustic curtailment control just presented.
5. Description of the current process of measurement

5.1. Norm for the commissioning control

Everything described in this section 5.1 comes from the current norm proposal 31-114 [32]. An acoustic campaign is conducted in several steps. The first one is to determine measurement locations around the wind farm and place microphones there. The so-called homogeneous classes are then defined according to the specificities of the field. Wind direction, day and night, season and other criteria can be used to characterize a given noise level. More details about defining homogeneous classes will be given in section 5.1.1. While wind turbines are stopped, existing noise is measured and data are classified in each homogeneous class defined previously. Wind turbines are then free to rotate again respecting the curtailment plan proposed in the development phase study. Ambient (or global) noise is measured at the same locations and also classified in the same homogeneous classes. Emergences and uncertainties are calculated for each homogeneous class. Because of the high uncertainty value (can reach 3dB which is the order of magnitude of the emergence threshold), a project cannot be proven conform but can only be proven non-conform.

5.1.1. Definition of terms and parameters

Wind speed bins are defined for each range of 1m/s centered on each integral value of the bin. The range is opened on the lower value and closed on the upper value. For example, the category 3m/s is defined as the bin \([2.5, 3.5]\) in m/s.

Wind direction categories are defined for each range of 60°, North being set as 0°. The wind direction bin will be opened on the lower value and closed on the upper value. For example, the category 30° is defined as the bin \([0, 60]\) in degrees.

Roughness length shows the irregularities of the terrain, slowing down the wind speed. It is defined according to the nature of the terrain and measured in meters. Some roughness classes and values can be seen from table 3-5 [33].

Homogeneous classes are defined in order to characterize a state of the noise environment. Noise measurements will then be plotted depending only on wind speed and no other parameter for each class. For example, ambient noise will be clearly different during the night and the day due to fauna and human activity. Classes can also be created according to the wind direction. Different criteria can be taken into account such as wind direction, day and night, time range, seasons, road traffic... They can be associated in order to create unique classes and be representative of the environment. Homogeneous classes are important since curtailment will be defined per class. For instance, curtailment is most of the time decided for night time and winter when existing noise is lower.

To illustrate this, an existing acoustic study at ABO Wind shows eight different classes:
- Wind coming from South-west \([180°, 270°]\), with one class for each following range: range 7am-8pm, 8pm-10pm, 10pm-6am and 6am-7am
- Wind coming from North-east \([0, 90°]\), with one class for each following range: range 7am-8pm, 8pm-10pm, 10pm-6am and 6am-7am
5.1.2. Noise and wind measurement

Wind speed and direction are measured using anemometers placed on the wind turbines, at hub height. If a permanent wind measurement mast is installed, data can also be taken from it. For sound level measurements, microphones are placed at houses situated the closest to the wind farm. If different groups of houses surround the project, one house is taken for each group and considered representative. Figure 28 shows microphone locations for a project in the department of Mayenne, France.

For a period of two weeks, sound level at houses and wind speed and direction at the wind mast are measured and recorded every 10 min. In this period of 10 minutes, the average wind speed is calculated and represents the value for the 10 minutes. Noise is measured every second (noted $L_{eq,1s}$) and only the median of these 600 measures (one measurement per second during 10 min, so 600 seconds) is taken as representing the whole 10 minutes. Said in a more technical way, the value represents the $L_{50}$ (median) of the $L_{eq,1s}$ during 10 minutes. Each 10 minutes sound level is then associated with the corresponding 10 minutes wind speed and direction value. In order to make the process repeatable and comparable, wind speed is standardized using a reference height of 10 m and a roughness length of 0.05 m. The calculation is explained below.
5.1.3. Calculation of standardized wind speed

If anemometers on wind turbines are used, the standardized wind speed is calculated as presented in the norm proposal 31-114\textsuperscript{(32)}:

\[
V_s = V(H) \frac{\ln \left( \frac{H}{Z_0} \right)}{\ln \left( \frac{H_{ref}}{Z_0} \right)}
\]  

(Equation 10)

With \(V_s\): standardized wind speed; \(H\): hub height (in m); \(V(H)\): wind speed at hub height (in m/s); \(h_{ref}\) the reference height (10m); \(Z_0\) the reference roughness length (0.05m)

If a wind mast measurement is used, the wind speed is measured at two different heights, \(h_1\) and \(h_2\), while respecting the following conditions:

(1) \(h_2 > h_1 > 10\text{m}\)  
(2) \(h_2 > \frac{H}{2}\)  
(3) \((h_2 - h_1)\) is maximum  
(4) \(h_2\) as close to \(H\) as possible

with \(H\) hub height. These conditions are made to limit the influence of roughness length and reduce approximations. Then, \(V_s\) is calculated with:

\[
V_s = \frac{\ln \left( \frac{10}{0.05} \right)}{\ln \left( \frac{H}{0.05} \right)} \times \left( V_1 + \frac{\ln \left( \frac{H}{h_1} \right)}{\ln \left( \frac{h_2}{h_1} \right)} \right) 
\]  

(Equation 11)

With notations previously defined and 10 corresponding to the reference height of 10m, and 0.05 the reference roughness length of 0.05m. \(V_1\) and \(V_2\) are the wind speed respectively at \(h_1\) and \(h_2\). Figure 29 illustrates the calculation. From the wind speeds at \(h_1\) and \(h_2\), the wind speed is calculated at hub height and standardized at 10m height.

![Figure 29 Principle of standardized wind speed calculation](reproduced from the norm 31-114)
5.1.4. Calculation and representation of existing noise

As described previously, base time range is defined as being 10min. For each range of 10min, a pair (average wind speed; median noise level) is calculated. These pairs are then reported on a graph, creating a scatter diagram. For each wind speed bin centered on the integer values, the median of all the noise levels reported in the bin is calculated. This wind speed bin noise level median is associated with the average wind speed calculated with the corresponding wind speeds of the bin. One value for each wind speed bin corresponding to the pair (bin average wind speed; bin median noise level) is then reported on the graph. The norm imposes that a minimum of 10 measurements for each wind speed bin is needed to determine this pair. Figure 30 shows a scatter diagram for one homogeneous class of the same project in the department of Mayenne. Points in red represent the calculated pairs (bin average wind speed; bin median noise level) for each bin.

![Image](image1.png)

**Figure 30** Existing noise scatter diagram according to wind speed for one microphone location and one homogeneous class

The average wind speed calculated for each bin usually does not correspond to the integral value of the bin but is slightly shifted to the left or right (example an average of 5.2m/s for the bin of 5m/s). In order to get the noise level at the integral value, an interpolation is used. The norm imposes to use the value of the previous or the next wind speed bin in the interpolation. The line drawn between the 2 points gives the value at the integral value. Figure 31 graphically shows an example using the previous value in the interpolation of the wind bin of 5m/s.

![Image](image2.png)

**Figure 31** Example of interpolation using the previous value for the wind category 5m/s
Once existing noise is measured and reported for each homogeneous class, a table per homogeneous class is obtained with the existing noise corresponding to each location for each wind speed bin. This is the reference characterizing the noise on the field before any modification of the environment.

5.1.5. Ambient noise measurement

After measuring existing noise, wind turbines are enabled again to rotate. If curtailment was estimated necessary in the development phase acoustic campaign, it will also be put in place at this moment. The same process as exiting noise is then used. Measurements are conducted during two weeks, classified in homogeneous classes and then plot on scatter diagrams. Pairs (bin average wind speed; bin median noise level) are calculated and interpolated on integral values with the same method. As for the existing noise, a table for each homogeneous class is obtained with the ambient noise corresponding to each location for each wind speed bin.

5.1.6. Emergence noise calculation

Once existing and ambient noise tables are obtained for each homogeneous class, location and wind speed bin, emergence noise can be calculated. The emergence is defined as:

\[ E(j) = L_{\text{amb}}(j) - L_{\text{exis}}(j) \]  

(Equation 12)

With:

- \( E(j) \): emergence indicator for the wind speed bin “j”
- \( L_{\text{amb}}(j) \): ambient noise level for the wind speed bin “j”
- \( L_{\text{exis}}(j) \): existing noise level for the wind speed bin “j”

5.1.7. Uncertainties

Three different uncertainties are calculated with formulas given by the norm proposal 31-114 [32]: the uncertainty of type A represents the distribution of the data set and the uncertainty of type B represents the measurement device uncertainties and the uncertainty of type C represents the total uncertainty. The uncertainties A and B are calculated differently for the absolute (ambient) noise levels (to be compared with the maximum of 60 and 70 dB(A) allowed) and for the emergence noise level (to be compared with the maximum of 3 and 5 dB(A) allowed).

**Uncertainties for existing and ambient noise level:**

The uncertainty of type A is calculated as followed for the ambient noise level:

\[ U_A(L_{\text{Amb}}(j)) = 1.858 \cdot t(L_{\text{Amb}}(j)) \cdot \frac{DMA(L_{\text{Amb}}(j))}{\sqrt{N(L_{\text{Amb}}(j))} - 1} \]  

(Equation 13)

The same formula is used for the existing noise level:

\[ U_A(L_{\text{exis}}(j)) = 1.858 \cdot t(L_{\text{exis}}(j)) \cdot \frac{DMA(L_{\text{exis}}(j))}{\sqrt{N(L_{\text{exis}}(j))} - 1} \]  

(Equation 14)

With:

- \( L_{\text{Amb}}(j) \): Ambient noise indicator for the wind category “j”
- \( L_{\text{exis}}(j) \): Existing noise indicator for the wind category “j”
- \( N(X(j)) \): Number of indicators of X(j) for the wind category “j”
- \( t(X(j)) \): corrective factor for small data sets X(j) for the wind category “j”

28
\[ t(X(j)) = \frac{2 \cdot N(X(j)) - 2}{2 \cdot N(X(j)) - 3} \]  
\[ DMA(X(j)) = Median(|X(j), i - Median(X(j), i)|) \]  

The uncertainty of type B is calculated as followed:

\[ U_B(L_{Amb}(j)) = \sqrt{\sum_k U_{Bk}(L_{Amb}(j))^2} \]  

Coefficients \( U_{Bk} \) are given by table 3, set by the norm.

### Table 3 Default values of type B uncertainties for ambient noise level measurements

<table>
<thead>
<tr>
<th>( U_{Bk} )</th>
<th>Origin</th>
<th>Default value</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{B1} )</td>
<td>Calibrating</td>
<td>0.20 dB (A)</td>
<td>Time maximum between 2 calibrating: 15 days</td>
</tr>
<tr>
<td>( U_{B2} )</td>
<td>Device</td>
<td>0.20 dB(A)</td>
<td></td>
</tr>
<tr>
<td>( U_{B3} )</td>
<td>Directivity</td>
<td>0.52 dB(A)</td>
<td>Default microphone directivity: vertical</td>
</tr>
<tr>
<td>( U_{B4} )</td>
<td>Frequency linearity</td>
<td>1.05 dB(A)</td>
<td></td>
</tr>
<tr>
<td>( U_{B5} )</td>
<td>Temperature and humidity</td>
<td>0.15 dB(A)</td>
<td></td>
</tr>
<tr>
<td>( U_{B6} )</td>
<td>Static pressure for one homogeneous class</td>
<td>0.25 dB(A)</td>
<td></td>
</tr>
<tr>
<td>( U_{B,\text{wind}} )</td>
<td>Wind perturbation</td>
<td>See below</td>
<td></td>
</tr>
</tbody>
</table>

The uncertainty due to the wind measurement is given by:

\[ U_{B,\text{wind}}(L_{Amb}(j)) = U_B(Wind(j)) \left( \frac{L_{Amb}(j + 1) - L_{Amb}(j - 1)}{2} \right) \]  
\[ U_B(Wind(j)) = \frac{V(H)}{V(h)} U'_B(Wind(j)) \]  
\[ U''_B(Wind(j)) = \sqrt{0.1^2 + (0.034 + 0.0034 V(j))^2 + (0.01 V(j))^2 + 0.03^2} \]

With:
V(H): wind speed measured at hub height H
V(h): wind speed measured at the highest anemometer position h

At the end, the total uncertainty (type C, called \( U_c \)) for global noise level is given by:

\[ U_c(L_{Amb}(j)) = \sqrt{U_A(L_{Amb}(j))^2 + U_B(L_{Amb}(j))^2} \]  
\[ U_c(L_{exis}(j)) = \sqrt{U_A(L_{exis}(j))^2 + U_B(L_{exis}(j))^2} \]
Uncertainties for emergence noise level (to be compared to the emergence noise thresholds allowed)

The uncertainty of type A is given by:

\[ U_A(E(j)) = \sqrt{U_A(L_{Amb}(j))^2 + U_A(L_{exist}(j))^2} \]  
(Equation 23)

With, as previously defined:

\( L_{Amb}(j) \) : Ambient noise indicator for the wind category « j »

\( L_{exist}(j) \) : Existing noise indicator for the wind category « j »

The uncertainty of type B is given by the same formula presented before but with different coefficients. These coefficients are presented in the table 4. It is considered that errors due to wind measurements cancel each other from the ambient noise measurements and existing noise measurements.

<table>
<thead>
<tr>
<th>( U_{Bk} )</th>
<th>Origin</th>
<th>Default value</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{B1} )</td>
<td>Calibrating</td>
<td>Not significant</td>
<td>Time maximum between 2 calibrating: 15 days</td>
</tr>
<tr>
<td>( U_{B2} )</td>
<td>Device</td>
<td>Not significant</td>
<td>Default microphone directivity: vertical</td>
</tr>
<tr>
<td>( U_{B3} )</td>
<td>Directivity</td>
<td>Not significant</td>
<td>Default microphone directivity: vertical</td>
</tr>
<tr>
<td>( U_{B4} )</td>
<td>Frequency linearity</td>
<td>( 1.05 \times \sqrt{2 - 2 \times 10^E/10} ) dB(A)</td>
<td>( E ) is the emergence, taken as positive or null</td>
</tr>
<tr>
<td>( U_{B5} )</td>
<td>Temperature and humidity</td>
<td>0.22 dB(A)</td>
<td></td>
</tr>
<tr>
<td>( U_{B6} )</td>
<td>Static pressure for one homogeneous class</td>
<td>0.24 dB(A)</td>
<td></td>
</tr>
<tr>
<td>( U_{B, wind} )</td>
<td>Wind perturbation</td>
<td>Not significant (canceling)</td>
<td></td>
</tr>
</tbody>
</table>

Finally:

\[ U_C(E(j)) = \sqrt{U_A(E(j))^2 + U_B(E(j))^2} \]  
(Equation 24)
5.1.8. Interpretation of uncertainties

Uncertainties previously described are used in order to compare the final emergence and ambient noise levels with the regulation. So far, the norm proposal defines a way to interpret and use them, allowing concluding on the non-conformity of the wind farm. It will probably not be included in the norm at the end but a specific document will be published to officialise the interpretation in the law. If the non-conformity is not proven, it is then considered that the wind farm is conforming. Uncertainties are distinguished if they are for ambient noise level or emergence noise level.

**Ambient noise level**
Parameters are set as followed:

- \( S_{QL} \): Threshold of uncertainty that cannot be exceeded to keep a good estimation quality. It is set at 3dB(A)

- \( L_{Amb}(j) \): Ambient noise indicator for the wind category « j » (for a given homogeneous class)

- \( L_{Amb}(j)* \): Ambient noise indicator exceeded with a certain confidence level for the wind category « j » (for a given homogeneous class). It is the value to compare with the regulations.

- \( U_c(L_{Amb}(j)) \): Total uncertainty value on the ambient noise level for the wind category « j ».
  It is called \( U_c \) in the following.

- \( U_B(L_{Amb}(j)) \): Measurement device uncertainty value on the ambient noise level for the wind category « j ».
  It is called \( U_B \) in the following.

**Threshold**: maximum ambient noise level given by the regulations: currently 60dB during the night and 70dB during the day

**K**: tolerance factor. It is taken as 1 if no other specification is given.

Two cases are then distinguished:

- If \( U_c > S_{QL} \)
  Measurements have to be continued and/or the homogeneous classes have to be precised in order to conclude on the exceeding or not of the threshold.

- If \( U_c \leq S_{QL} \)
  The following calculations are done:

  \[
  B = \min(U_B, 1.9) \\
  L_{Amb}(j)* = L_{Amb}(j) - K \cdot U_c + K \cdot \max(U_c - B, 0) \cdot S_{QL} / (S_{QL} - B) \quad \text{(Equation 25)}
  \]

  If \( L_{Amb}(j)* > \text{Threshold} \), the ambient noise level exceeds the limit set by the regulations. Otherwise, the non-conformity cannot be proven (the project is then considered as conforming).
**Emergence noise level**

Parameters are set as followed:

- **S<sub>QL</sub>**: Threshold of uncertainty that cannot be exceeded to keep a good estimation quality. It is set at 3dB(A)

- **E(j)**: Emergence noise indicator for the wind category « j » (for a given homogeneous class)

- **E(j)***: Emergence noise indicator exceeded with a certain confidence level for the wind category « j » (for a given homogeneous class). It is the value to compare with the regulations.

- **U<sub>C</sub>(E(j))**: Total uncertainty value on the emergence noise level for the wind category « j ». It is called U<sub>C</sub> in the following.

- **U<sub>B</sub>(E(j))**: Measurement device uncertainty value on the emergence noise level for the wind category « j ». It is called U<sub>B</sub> in the following.

- **Threshold**: maximum emergence noise level given by the regulations: currently 3dB during the night and 5dB during the day

- **K**: tolerance factor. It is taken as 1 if no other specification is given.

Two cases are then distinguished:

- If **U<sub>C</sub> > S<sub>QL</sub>**
  
  Measurements have to be continued and/or the homogeneous classes have to be precised in order to conclude on the exceeding or not of the threshold.

- If **U<sub>C</sub> <= S<sub>QL</sub>**
  
  The following calculations are done:

  \[
  B = \min(U_B, 1,9) \\
  E(j)* = E(j) - K \cdot U_C + K \cdot \max(U_C - B, 0) \cdot \frac{S_{QL}}{S_{QL} - B}
  \]  

  (Equation 26)

  If **E(j)* > Threshold**, the emergence noise level exceeds the limit set by the regulation. Otherwise, the non-conformity cannot be proven (the project is then considered as conforming).

  These statistics unilateral tests are done with a tolerance factor of 1, corresponding to confidence degree of 84.1% for a Gaussian distribution of the uncertainties.

  Every ambient noise levels are controlled and validated if they are not over 60dB(A) at night and 70dB(A) during the day in the perimeter defined by the law. Most of the time, these levels are respected. For emergence noise levels, additional curtailment will be decided if some points are over the threshold. If curtailment is already in place and seems too restrictive, it can be slightly modified but it will be harder to justify to the administration than increasing it.
5.2. Development phase study

The acoustic campaign described previously is conducted when the wind farm is built. The method described is the method imposed by the project of norm 31-114. At the development phase, freedom is given to the acoustic consultant to realize a model which should be as close as reality and field measurement as possible. Obviously, some hypotheses from the norm are considered since this norm will be the frame of the commissioning acoustic control. But some conditions and criteria can be added in order to get closer to reality. Some parts of the norm such as the uncertainties on ambient noise cannot be used since they are simulated and not measured at the development phase.

Currently, acoustic consultants try to be as close to the norm as possible, even at the development phase. So existing noise and wind speed measurements are so far done in the same way as described previously. Calculations for standardized wind speed are also done in the same way. However, as it will be shown in the next section, some hypotheses used in the norm are not adapted at the development phase and more reliable estimations could be made. The next section will propose improvements to the current method. In the current section, the way of modeling and simulating the emission noise from wind turbines is presented.

5.2.1. Simulation

The first step is to estimate noise emission from each wind turbine. This is done using a table given in the specifications of the supplier. An example is shown on figure 32. Noise emissions are given for each wind speed both standardized at 10m and at hub height. For each standardized wind speed bin at 10m measured at the wind mast location, a value of noise emission is attributed. So far, all turbines are considered emitting the same noise level at the same mast measurement wind speed. For the wind speed bin of 4m/s and a hub height of 80m for example, it is considered that all turbines emit 96.3dB(A) no matter their location. In the simulation, all turbines will then be taken as an emission source of the corresponding level for each wind speed.

<table>
<thead>
<tr>
<th>W_{10} [m/s]</th>
<th>W_9 [m/s]</th>
<th>SPL [dB(A)]</th>
<th>W_9 [m/s]</th>
<th>SPL [dB(A)]</th>
<th>W_9 [m/s]</th>
<th>SPL [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.2</td>
<td>95.8</td>
<td>4.3</td>
<td>95.8</td>
<td>4.5</td>
<td>95.8</td>
</tr>
<tr>
<td>3.5</td>
<td>4.9</td>
<td>95.8</td>
<td>5.0</td>
<td>95.8</td>
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<td>95.8</td>
</tr>
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<td>98.0</td>
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<td>100.6</td>
</tr>
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<td>5</td>
<td>7.0</td>
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<td>7.1</td>
<td>101.9</td>
<td>7.5</td>
<td>103.0</td>
</tr>
<tr>
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<td>7.9</td>
<td>104.1</td>
<td>8.2</td>
<td>105.2</td>
</tr>
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<td>8.4</td>
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<td>106.0</td>
</tr>
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<td>9.7</td>
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<td>106.0</td>
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<td>106.0</td>
</tr>
<tr>
<td>8.5</td>
<td>11.9</td>
<td>106.0</td>
<td>12.1</td>
<td>106.0</td>
<td>12.7</td>
<td>106.0</td>
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<td>106.0</td>
<td>12.9</td>
<td>106.0</td>
<td>13.5</td>
<td>106.0</td>
</tr>
<tr>
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<td>13.2</td>
<td>106.0</td>
<td>13.6</td>
<td>106.0</td>
<td>14.2</td>
<td>106.0</td>
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<td>13.9</td>
<td>106.0</td>
<td>14.3</td>
<td>106.0</td>
<td>15.0</td>
<td>106.0</td>
</tr>
</tbody>
</table>

Figure 32 Noise emission specifications given by the supplier for the turbine used in the project of Mayenne
Several softwares exist in order to model acoustic emission and propagation such as CadnaA\textsuperscript{©}, SoundPLAN\textsuperscript{©} and AcouS PROPA\textsuperscript{©} just to cite some. From the turbine noise emission given by the supplier, a simulation is used to estimate the noise made at the microphone locations. Several acoustic propagation models exist. One which is usually used is defined in the norm ISO 9613-2. Noise propagation is defined by the following equation:

\[ L_p = L_w - A_{dv} - A_{atm} - A_{ground} - A_{screen} - A_{ref} \]  \hspace{1cm} (Equation 27)

The A terms correspond to attenuation due to the ground, the diffraction and other environmental factors. A meteorological correction term is added for locations at a minimum distance of 10 times the noise source height. Given that noise is considered being generated at hub height (around 100m), meteorological parameters are not taken into account before 1km distance. Microphones placed at houses are usually at a distance lower than this one. So wind direction in particular is not taken into account in the simulation. Other parameters such as the directivity of the noise and the number of reflection are included and decided by the acoustician consultant in his work.

From the existing noise that was measured on the field and the estimation of noise emission from all wind turbines, the software simulates noise propagation and lead to ambient noise level results at each microphone location for each wind speed bin. Simulation is done for each homogeneous class previously defined. It results in a table with simulated ambient noise for each homogeneous class with each location and wind speed. These values are compared with the existing noise and emergences are calculated and shown in equivalent tables. The acoustic consultant will then use these tables to propose curtailment in case of emergence exceeding the threshold. No uncertainty is currently considered at the development phase.

The acoustician knows the contribution of each wind turbine to the noise emitted to one location. Therefore he first tries to reduce the power of the turbine contributing the most and observes the impact on noise emergence level. If this is not sufficient, a higher noise reduction mode is used or noise reduction mode is applied to another turbine contributing significantly. By an iteration process, emergences are decreased. Stopping a machine is always avoided if possible. It would be preferred curtailing three machines than stopping one. As described previously in the report, energy production impact is much higher when stopping a turbine than curtailing it. If all noise contributing turbines have been curtailed to their maximum reduction mode, it is then decided to stop a machine and others if needed, until reaching an emergence noise level under the authorized threshold. Once again, this process is done for each homogeneous class. One table of curtailment for one homogeneous class is presented on figure 33. This homogeneous class corresponds to summer, at night time (between 10pm and 7am) and for a wind direction from East/South-East until West/North-West. For ambient noise levels above 35dB(A), emergences above 3dB(A) are shown in red.
High emergences can be noted for the wind speed bins of 5, 6 and 7 m/s. It results in a need of stopping 2 machines and curtailing 3 others for the wind speed of 5 m/s. For the 6 and 7 m/s wind speed bins, 5 turbines need to be stopped and the last one is curtailed. This plan is the first estimation for a first scenario implantation and is actually very negative. The energy resulting from this plan has not been precisely estimated but is definitely not acceptable. Turbines will have to be located differently, the model of turbine will have to be changed or fewer turbines will need to be installed.

We can see some emergence values of 3.5 or 4 dB(A) (superior to 3 dB(A) allowed at night) but could be fixed in an easier way. As explained in the section defining the problematic, getting a more reliable model would here result in more favorable results. These small emergence values would then probably disappear. Using uncertainties could also justly reducing curtailment time, predicting a more favorable measurement control at commissioning.
6. **Solutions proposed to improve the reliability of the development phase acoustic campaign**

Before describing some solutions, the concept of emergence has to be well understood. From the developer point of view, the objective is obviously to respect the regulation and the comfort of inhabitants but also to get as little emergences as possible to reduce curtailment time. Applying this to the noise parameters we know, it means expecting a high existing noise and a low noise emission from the wind turbines. The objective is clearly to get as close to reality as possible but it has to be kept in mind that an increased existing noise and a reduced emission noise from the wind turbine will be seen as a benefit for the developer.

6.1. **The time of the measurements**

6.1.1. **The current situation**

Acoustic measurements show different noise levels according to the time in the year, or with other words, according to the season. This is mostly due to a difference of activity from the local fauna and difference of vegetation. In winter, animals are mostly quiet and trees have less leaves, generating less existing noise. In summer, a higher animal activity is usually observed and vegetation leads to more noise emission. So far, measurements are done two times in one year: one during winter and one during summer or spring. Homogeneous classes are then determined according to these two studies but the limit between winter and spring is not clear. The fauna activity and the noise from the wind in the leaves do not always correspond to the traditional time ranges of seasons we know. For example, it is not because summer officially starts on the 21st of June that animals will not be active before and generate noise. No specific criteria except the official season dates are used today. It can lead to people discomfort in some periods or to unnecessary curtailment estimations and thus an important loss in other periods.

6.1.2. **Proposed solution**

So far, the period of measurement for the acoustic campaign is only chosen in order to avoid non-representative factors (according to the norm 31-114) such as rain and specific human activities. The environment itself which directly influences the existing noise is not taken into account into the choice of the time of the measurement.

In order to get measurements as close to reality as possible, it is then proposed to link the acoustic study with the environmental one. The environment can be characterized according to the type of fauna and flora. Before realizing acoustic measurements, the year can be divided into main periods corresponding to the activity of the fauna or the type of flora existing on site. For instance, the period when trees have leaves will correspond to a loud period. The activity of animals also influences greatly the existing noise level. Taking the example of a previous project, the sound made by crickets was increasing the sound level by up to 20dB(A) during few hours and for several months. Observations done by the environmental consultant on site would then lead to the choice of the adapted periods to realize the acoustic study. If big differences are foreseen, it can be interesting to realize more than only two periods of measurements or to make them during these different periods.
This question of acoustic depending on the animal activity and the fauna characteristics has been raised and discussed with the environment consultant working for the project in the department of Mayenne. The consultant confirmed that some periods could be distinguished according to the type of animals present on site. Some species are singing during a precise period which usually corresponds to the reproductive period. Taking the example of the same project, three main types of animals are present on site and generating noise at different periods. The orthoptera are active mostly from June to September, emitting a noise with their little wings. The amphibian are singing from June to September as well. Finally, the birds are noisier from February to June. It is also proposed to consider human activities such as road traffic and harvest time when using tractors. Putting these data together, a diagram showed on figure 34 enables us to easily estimate the noisiest and quietest period.

Given these data, the noisiest month would definitely be the month of June or July. On the contrary, it is estimated to be quieter from October to January. The acoustic studies conducted for this project were done in November and in May. November seems quite adapted to characterize the existing noise in winter. But in May, animals may have not been all active, thus underestimating the existing noise. It has to be kept in mind that these data are only estimations and the activity always depends on the year climate. If summer comes earlier, the fauna activity will be high sooner and the other way around if it is a cold year. These elements are just giving an overall idea but should not be taken as granted. It can at least give arguments to the choice of the period of measurement.

This question of seasonality can also lead to determine in a more precise way the homogeneous class periods for winter and summer. According to the diagram with animal activity added to the knowledge of the type of flora on site, “acoustic” winter and summer periods could be decided. In the case of the project in Mayenne, we could distinguish two periods: the “winter period” with no activity at all, from October to January and the “summer period” with higher activity (at least one active specie), from February to September. Instead of defining homogeneous class periods randomly or only following the classical seasons known in France, it would at least give arguments for defining them. In the case of the project in Mayenne, one more month is added to the summer period compared to the classical seasons. It is then an advantage for the developer since curtailment is usually less restrictive in summer. It can exist cases when summer activity is shorter. Every project is specific but if ABO Wind prefers staying optimistic, the most advantageous situation could be chosen depending on the length of the “acoustic summer” determined from the fauna activity.

As a conclusion on this point, it is proposed to systematically lead a pre-diagnostic from the environmental consultant at the first place. A table with fauna activity, human activity and flora noise potential would be made for deciding the adapted periods of acoustic measurements. By adapted we mean the maximum noise immission in summer and the minimum noise immission in winter. This will lead to measurements of minimum and maximum noise levels during one year and will allow defining winter and summer periods for homogeneous classes.
6.1.3. Potential benefits

The benefits are highly dependent on the project and no rule can be defined. However, a rough estimation can be made for the case presented previously, given some assumptions. If we only consider the figure 34, we could consider that “acoustic summer” goes from February to September and “acoustic winter” from October to end of January. Compared to the usual 6 months of “summer” and “winter” defined for the curtailment, it would then be 2 more months for summer. In case of the project in Mayenne, and in many other cases, turbines usually have to be shut down during the night in the winter season. Considering that the night lasts from 10pm to 7am (9 hours), these two months added to “summer season” would then represent an additional availability of 504 hours (5% of the year). It does not mean that they would rotate all this time but they would be able to if the wind is strong enough. Using the capacity factor, the average wind speed and the swept area by the turbine, it can roughly give an estimation of energy production during these 2 months using the following formula:

\[ E_{loss} = h_{RS} \times C_p \times \frac{1}{2} \rho AV^3 \]  

(Equation 28)

With \( C_p = \frac{P_{turbine}}{P_{wind}} \) and calculated as 36.3% for the given project by the internal wind department of ABO Wind. The average wind speed was estimated as being 6.38m/s at hub height for a swept area of 10207m². Air density is taken as 1.2kg/m³.

It gives an energy production estimation of 291MWh on this 2 months period. Given an electricity price of 8.2cts of euro per kWh, it represents around 24k€ per year and per turbine that should have been shut down in this 2 months winter period. It is a very rough estimation but it still shows that this seasonality definition is significant.

6.2. Calculation and simulation assumptions

Calculation assumptions can lead to slightly different results. If the impact of each of them does not seem relevant, the cumulated impact of all of these assumptions can be significant. The project in Mayenne, currently under development, is going to be used as a case study. Wind measurements were done by ABO Wind with a mast installed on the field during two years. Acoustic measurements were completed a few weeks ago by the engineering consultant firm. Their data will be used for the different calculations.

6.2.1. Roughness length

6.2.1.1. The current situation

The norm requires calculating the roughness length every ten minutes, for each set of value. It is done indirectly in the formula presented by the norm by using every 10 minutes the wind speeds at two different heights. The wind department of ABO Wind calculates the roughness length upfront using all wind measurement values and keeps it constant. It is proposed to compare these two methods and see which should be used to be as close to reality as possible.
6.2.1.2. **Proposed solution**

The first method used by the wind department of ABO Wind is to calculate the roughness length at first. Using wind data from two heights, the roughness length is estimated and kept constant for the rest of the calculations. Standardized wind speeds are then calculated using the following formula:

\[
V_s = V_2 \frac{\ln \left( \frac{10}{0.05} \right) \ln \left( \frac{H}{r} \right)}{\ln \left( \frac{H}{0.05} \right) \ln \left( \frac{h_2}{r} \right)}
\]

(Equation 29)

With \(V_s\): standardized wind speed and \(V_2\): wind speed at height \(h_2\). 10 and 0.05 in the logarithm correspond to a standardized height of 10m and a standardized roughness length of 0.05m. \(H\) is the hub height and \(h_2\) the height at the highest wind measurement point of the wind mast. Finally, \(r\) is the estimated roughness length from wind data.

The second method, following the norm calculation, does not calculate the roughness length but integrate it in the calculation. The standardized wind speed is then calculated as followed:

\[
V_s = \frac{\ln \left( \frac{10}{0.05} \right)}{\ln \left( \frac{H}{0.05} \right)} \left[ V_1 + \frac{\ln \left( \frac{H}{h_1} \right)}{\ln \left( \frac{h_2}{h_1} \right)} (V_2 - V_1) \right]
\]

(Equation 30)

With the same notations and \(V_1\): wind speed at height \(h_1\) with \(h_1\): height at the lower wind measurement point of the wind mast. Using these two methods, we calculate all standardized wind speeds and compare the results. The overall average difference is interesting to assess the global impact but the maximal difference between the two methods can also give a good indication. As described before, some wind speed ranges are more sensitive than others and a high difference even on few measurements could also be interesting.

6.2.1.3. **Potential benefit**

The overall average difference between the two methods is zero. There is globally no difference between the two ways of calculating the standardized wind speed. The maximum difference of 0.34m/s is quite small. It can be concluded that the two calculations are equivalent and will not make any difference on the final result. The differences are plotted and shown on figure 35. The difference is clearly not significant and cannot be used to improve the results. As a choice, it is then better using the formula given by the norm to be sure to respect its conditions.

![Distribution of the difference](image-url)

*Figure 35 Difference distribution between the two methods of calculating roughness length*
6.2.2. Interpolation

6.2.2.1. The current situation

As described in the acoustic campaign process, once wind measurements are standardized and associated to a sound level, they have to be interpolated to wind speed integral values [3; 4; 5; 6…] m/s. So far, acoustic consulting firms use linear or polynomial regression to interpolate wind speeds to integer values. As explained in the description of the acoustic control, the norm proposes a different method using the value of the next or previous wind speed category within the interpolation. A comparison between both methods is presented below.

6.2.2.2. Proposed solution

The norm gives a new way of doing the interpolation. Using the data from the same project in Mayenne, interpolation is done using the two different methods. In the acoustic study considered, 8 locations at houses near the wind farm were chosen to measure noise level. For each of them, interpolation is needed for all wind speed values associated to a noise emission.

6.2.2.3. Potential benefit

In the chosen case study, we focus on winter acoustic measurements with only two homogeneous classes defined. Calculations are done separately for the two classes and differences between current regression method and the norm method are presented on figure 36.

<table>
<thead>
<tr>
<th>Homogeneous class 1</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1 (without rain)</td>
<td>0.6</td>
<td>0.8</td>
<td>-0.1</td>
<td>-1.0</td>
<td>-1.6</td>
<td>1.5</td>
<td>-1.4</td>
<td>1.1</td>
<td>-0.18</td>
</tr>
<tr>
<td>Location 1 (with rain)</td>
<td>0.6</td>
<td>0.8</td>
<td>-0.4</td>
<td>-1.1</td>
<td>-1.0</td>
<td>1.5</td>
<td>-1.0</td>
<td>1.2</td>
<td>0.61</td>
</tr>
<tr>
<td>Location 2</td>
<td>1.5</td>
<td>0.6</td>
<td>-0.3</td>
<td>-1.1</td>
<td>-0.5</td>
<td>0.1</td>
<td>0.4</td>
<td>0.2</td>
<td>0.81</td>
</tr>
<tr>
<td>Location 3</td>
<td>1.0</td>
<td>0.0</td>
<td>-0.1</td>
<td>-0.9</td>
<td>-1.1</td>
<td>1.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.34</td>
</tr>
<tr>
<td>Location 4</td>
<td>1.1</td>
<td>-0.5</td>
<td>-0.3</td>
<td>-0.5</td>
<td>-0.7</td>
<td>0.9</td>
<td>0.3</td>
<td>-0.3</td>
<td>-0.10</td>
</tr>
<tr>
<td>Location 5</td>
<td>1.7</td>
<td>-0.6</td>
<td>-1.2</td>
<td>0.0</td>
<td>-1.1</td>
<td>0.1</td>
<td>0.5</td>
<td>0.2</td>
<td>0.22</td>
</tr>
<tr>
<td>Location 6</td>
<td>2.0</td>
<td>-0.2</td>
<td>0.0</td>
<td>-0.4</td>
<td>-2.4</td>
<td>0.0</td>
<td>-0.3</td>
<td>2.1</td>
<td>-0.06</td>
</tr>
<tr>
<td>Location 7</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.8</td>
<td>-0.3</td>
<td>-0.2</td>
<td>1.1</td>
<td>0.2</td>
<td>-1.1</td>
<td>-0.62</td>
</tr>
<tr>
<td>Location 8</td>
<td>0.6</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.5</td>
<td>-2.3</td>
<td>1.5</td>
<td>0.0</td>
<td>0.2</td>
<td>-0.30</td>
</tr>
<tr>
<td>Total</td>
<td>3.3</td>
<td>1.3</td>
<td>-3.0</td>
<td>-0.7</td>
<td>-11.0</td>
<td>7.0</td>
<td>-0.3</td>
<td>3.3</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Homogeneous class 2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1 (without rain)</td>
<td>0.7</td>
<td>-1.8</td>
<td>0.9</td>
<td>-0.7</td>
<td>0.6</td>
<td>0.7</td>
<td>-0.5</td>
<td>-1.3</td>
<td>-1.75</td>
</tr>
<tr>
<td>Location 1 (with rain)</td>
<td>0.2</td>
<td>-0.3</td>
<td>0.0</td>
<td>-0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.0</td>
<td>1.14</td>
</tr>
<tr>
<td>Location 2</td>
<td>1.1</td>
<td>-2.1</td>
<td>0.4</td>
<td>0.1</td>
<td>-1.5</td>
<td>1.1</td>
<td>3.6</td>
<td>-4.2</td>
<td>-1.50</td>
</tr>
<tr>
<td>Location 3</td>
<td>-0.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.8</td>
<td>-0.9</td>
<td>-2.0</td>
<td>3.2</td>
<td>-2.1</td>
<td>-0.66</td>
</tr>
<tr>
<td>Location 4</td>
<td>3.4</td>
<td>-2.7</td>
<td>-1.0</td>
<td>-2.2</td>
<td>-0.6</td>
<td>0.6</td>
<td>1.4</td>
<td>-0.2</td>
<td>-1.17</td>
</tr>
<tr>
<td>Location 5</td>
<td>-2.5</td>
<td>2.0</td>
<td>0.4</td>
<td>-0.8</td>
<td>-0.9</td>
<td>1.6</td>
<td>1.9</td>
<td>-1.2</td>
<td>-0.68</td>
</tr>
<tr>
<td>Location 6</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>-0.7</td>
<td>-0.2</td>
<td>0.8</td>
<td>0.1</td>
<td>-1.3</td>
<td>-0.87</td>
</tr>
<tr>
<td>Location 7</td>
<td>4.9</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.5</td>
<td>1.1</td>
<td>3.9</td>
<td>-2.5</td>
<td>4.28</td>
</tr>
<tr>
<td>Location 8</td>
<td>-1.2</td>
<td>2.6</td>
<td>0.5</td>
<td>-0.2</td>
<td>-3.6</td>
<td>0.5</td>
<td>0.2</td>
<td>-1.2</td>
<td>-0.31</td>
</tr>
<tr>
<td>Total</td>
<td>4.5</td>
<td>-5.4</td>
<td>1.4</td>
<td>1.7</td>
<td>-6.1</td>
<td>4.3</td>
<td>12.6</td>
<td>-15.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Légend:
- Norm being favorable (louder existing noise)
- Norm being unfavorable (quieter existing noise)

Figure 36 Differences (in dB(A)) between the regression and the norm methods
Since noise emission regulation imposes a limit of emergence, the higher the existing noise, the better for the developer. Thus, having a louder existing noise would here be considered as an advantage. However, results presented show on the contrary a quieter sound level. At first, this should then be taken as unfavourable criteria. It should be taken into account in order to be closer to what will be done when commissioning the wind farm and assessing the noise level. Some values are significant and could definitely lead to more curtailment or on the contrary reduce curtailment time.

This result is mostly dependant on the field. Given this method, it is clear that the norm interpolation will be favourable if the raw values are above the regression line. It then means that the existing noise would be slightly higher and thus considered as favourable for the developer. On the contrary, if the raw value is below the regression line, it would be favourable to use the regression line to get a higher value of existing noise. In the case of the project in Mayenne, average wind speeds are mostly below the regression line. This is illustrated on figure 37 with an example for the homogeneous class 1 at location 1.

The blue points represent the raw values of [wind speed; noise level] without interpolation. The black line is the regression line used so far by acoustic consultants to interpolate to integral values. The table on figure 37 presents the difference between the interpolation done with the regression line and the one done using the norm principle. It can be easily seen that the sign of the difference depends on the position to the regression line. Thus, it is not possible to consider this method as favourable or unfavourable. However, the norm method should be used since significant differences exist, even more at the sensitive wind speeds of 6m/s and 7m/s.

<table>
<thead>
<tr>
<th>Vs</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference</td>
<td>2.0</td>
<td>-0.1</td>
<td>0.3</td>
<td>-1.9</td>
<td>-2.6</td>
<td>0.8</td>
<td>-0.2</td>
<td>0.8</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

_Figure 37 Link between the regression line and the calculation differences_
6.2.3. Topography

6.2.3.1. The current situation

Another opportunity of improvement is to use a model closer to the reality for the emission and propagation of the noise from the wind turbines. The norm assumes a ground level identical for the wind measurement mast and all wind turbines. The wind speeds measured by the mast on the field are considered as being the same at all wind turbine hubs. Even if wind turbines are not at the same altitude, a wind speed of 4m/s at the wind mast will still be considered as 4m/s at all wind turbines. In reality, wind speed will be lower at hub height if altitude is lower than the mast measure device. Therefore, the noise emission from wind turbines experiencing a lower wind speed will also be smaller. It is illustrated on figure 38.

6.2.3.2. Proposed solution

As shown on figure 38, the norm requires calculating the wind speed at hub height using the measures at \( h_1 \) and \( h_2 \) and then standardizing it using the standard roughness length and height. On figure 38, it is considered that the wind turbine is at the same elevation as the wind mast but it is usually not the case. Instead of using the same hub height for all wind turbines, it is then proposed to take the hub height plus the difference of elevation. Instead of only one calculation for the whole wind farm, one calculation is done for each wind turbine.

In this case, the standardized wind speed reference is still the same, calculated according to figure 38 at the wind mast location. Instead of directly considering this wind speed at each wind turbine and use the corresponding noise emission, the wind speed is recalculated at each hub first. Given one standardized wind speed at the wind mast, it will correspond to a slightly different wind speed at each hub at the same moment. Using the difference of elevation, wind speed at each hub is recalculated and the noise emission is determined according to these speeds.
6.2.3.3. **Potential benefit**

The calculation has been done using the same case study in Mayenne and shown below. This test is independent from the wind resource of the field since standardized wind speeds are used. This test will enable us to quantify the impact of the difference of elevation between hubs and the wind mast. It is however dependent on the noise emissions declared by the supplier in the specifications.

The first column of figure 39 shows the standardized wind speed at the wind mast location. The second column shows the equivalent wind speed calculated at the reference hub height of 93m, height that was also used to standardize wind speeds during existing noise measurements. Until now, the first column only was used to determine the noise emitted by each wind turbine without making any difference between them. Noise emissions were read using the standardized wind speed at 10m in the specifications given by the supplier and shown in Annex 1.

It is now proposed to use hub height wind speeds, which are coming from standardized wind speeds, to determine noise emission from each wind turbine. Figure 40 shows the results of wind speed calculations taking into account the elevation difference with the wind mast. Hub height noise emissions read in the specifications (Ws) or interpolated with a linear regression are then used. Since the wind turbine E1 is at the same height as the wind mast, it will then be taken as the reference to compare sound levels. In the current acoustic studies, all wind turbines would be considered as emitting the same noise as E1 because the wind speed is assumed to be the same all over the field.

<table>
<thead>
<tr>
<th>Wind mast</th>
<th>H-H (93m) wind speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.84</td>
</tr>
<tr>
<td>3</td>
<td>4.26</td>
</tr>
<tr>
<td>4</td>
<td>5.68</td>
</tr>
<tr>
<td>5</td>
<td>7.10</td>
</tr>
<tr>
<td>6</td>
<td>8.53</td>
</tr>
<tr>
<td>7</td>
<td>9.95</td>
</tr>
<tr>
<td>8</td>
<td>11.37</td>
</tr>
<tr>
<td>9</td>
<td>12.79</td>
</tr>
<tr>
<td>10</td>
<td>14.21</td>
</tr>
</tbody>
</table>

Figure 39 Standardized wind speeds (at 10m) and at the reference hub height
It can be seen on figure 40 that on all wind turbines, improvements are seen only on the wind speed bins of 4, 5 and 6 m/s which are very sensitive to curtailment. The maximum difference is about 0.9 dB(A) for the wind speed bin of 5 m/s at E3. Given the sensitivity of this wind speed bin, reducing the potential noise emission by almost 1 dB(A) can be significant. By cumulating all these sound levels for each wind turbine, a maximum of 2.1 dB(A) of difference is found for E3, which is the lowest hub compared to the wind mast. Linking these noise emission differences to the elevation difference, it can be estimated that for each meter below the reference elevation, the noise emission is reduced by around 0.1 dB(A). For the 5 m/s bin, it represents around -0.05 dB(A)/meter. For an elevation difference of 30 m which is usual, an overall difference of 3 dB(A) is significant. It could represent up to 1.5 dB(A) of difference for the wind speed bin of 5 m/s, which can be enough to avoid stopping a turbine.

It is very hard to give financial gain estimation since it is highly dependent on the field and on the project. However, taking the same method as for the seasonality calculation, we can have a rough estimation of the order of price it represents. We consider the turbine would not be stopped but only curtailed during all nights of the whole year (curtailment is usually defined for nights only). A coefficient of curtailment of 20% loss compared to full power (taken from figures 26 and 27 at 7 m/s wind speed) is added to the formula used in the seasonality calculation, given the following formula:

\[ E_{\text{loss}} = (1 - C_{\text{curtailment}}) \cdot hrs \cdot C_p \cdot \frac{1}{2} \rho A V^3_{\text{mean}} \]  \hspace{1cm} \text{(Equation 31)}
The number of hours is then equal to 9hrs/day times 365 days giving 3285hrs per year. The same $C_p$ (36.3%), $V_{mean}$ (6.38m/s), $A$ (10207m²) and $\rho$ (1.2kg/m³) are used. And $C_{curtailment} = 20\%$. It gives an energy production of 1517MWh/year representing a financial value of 124 410€/year/turbine that would be running in a noise reduction mode instead of being shut down. This result has to be used carefully and only gives a rough estimation. If emergences are largely exceeded, an improvement due to this topography parameter will not prevent from shutting down the turbine. This is then valid only in case a turbine slightly exceeds the emergence threshold.

6.3. Uncertainties

6.3.1.1. The current situation

So far, measurement uncertainties are defined only partially in the norm 31-114. Acoustic consultants calculate them during the commissioning acoustic campaign but do not use them in the results because nothing indicates how they should be interpreted. However, this interpretation should be defined in the coming months and uncertainty calculations should also be defined soon. ABO Wind participates in the national work group regarding acoustic assessment and just had access to the last version of the norm, which is not official yet. Each part of the norm that has been described in this report is coming from this new version that is not official yet but should be soon. It is essential to take it into account from now in order to be prepared when it is officially published.

6.3.1.2. Proposed solution

However, at a development phase stage, no uncertainties are used so far. The ones defined in the norm for the commissioning study could eventually be considered at the development phase but only for the existing noise since the rest is simulated. Due to this simulation, other uncertainties that are obviously not presented in the norm can be defined. The first one is linked to the noise emission values displayed by the wind turbine supplier. According to confidential supplier reports on acoustic emission assessment from their turbines, uncertainties are in between 1 and 2dB. The other uncertainty that needs to be taken into account is the simulation uncertainty. The model itself cannot be perfect and also presents a significant uncertainty between 2 and 5dB according to acoustic consultants and previous empirical data. Uncertainties on the turbine emission and on the simulation can be combined to give the uncertainty on the total noise emission from wind turbines at the microphone location. The uncertainty on existing noise defined in the norm can be used for the existing noise level at the same microphone location. These two noise levels with their uncertainties allow calculating the ambient noise level with an associated uncertainty. By comparing this to the previous existing noise level and adding again the uncertainties, it finally gives the emergence level associated with the final uncertainty. Figure 41 and 42 summarize these uncertainties and the process of calculation for both the commissioning phase (applying the norm) and the development phase. To be valid, a noise measure has to get an uncertainty smaller then a maximum value. So far, the norm defines this maximum uncertainty as 3dB.
Figure 41 Measurement validation for the commissioning acoustic campaign (as defined in the norm 31-114 and presented in section 5.1.7)
As far as it is known today, no wind power developer has used uncertainties in their acoustic study during the development phase. This report then proposes a method to calculate them and consider them in the results of emergence noise. For the existing noise uncertainty, it is proposed to use the formulas described in the norm and showed previously. For the ambient noise calculation, the formula of the norm can obviously not be used since it is simulated and not measured. For cumulating the uncertainty due to the supplier and due to the simulation, it is proposed to use standard deviation.

As described in the simulation part, propagation of the sound is defined by the formula:

\[ L_p = L_w - A_{div} - A_{atm} - A_{ground} - A_{screen} - A_{ref} \]  \hspace{1cm} (Equation 32)

Considering the uncertainties of the simulation on the A coefficients, it is then a simple addition between the different terms. So the emission noise uncertainty can be calculated with standard deviation as followed: 

Figure 42 Uncertainty use in the process of emergence noise calculation at the development phase
With $U_m$ the supplier uncertainty and $U_s$ the simulation uncertainty. Then, we know that ambient noise will be calculated using the emission noise simulated and the existing noise measured. Since they are sound levels, they are added as indicated below:

$$L_{Amb} = 10\log \left(10^{\frac{L_{exis}}{10}} + 10^{\frac{L_{turbines}}{10}}\right) \tag{Equation 34}$$

Equation 34 is not a simple addition anymore; the quadratic sum of existing uncertainty and turbine emission uncertainty does not apply here. $L_{Amb}$ can be seen as a function of two independent variables $L_{exis}$ and $L_{turbines}$. The uncertainty associated with a general function of two variables is given by the law of propagation of uncertainty and is expressed as the quadratic sum of the partial derivatives times each respective uncertainty (equation 35).

$$U_{Amb}(L_{exis}, L_{turbines}) = \sqrt{\left(\frac{\partial L_{Amb}}{\partial L_{exis}} U_{exis}\right)^2 + \left(\frac{\partial L_{Amb}}{\partial L_{turbines}} U_{turbines}\right)^2} \tag{Equation 35}$$

In order to make the calculation easier to follow, let us define two functions $f$ and $g$ so that $L_{Amb} = f \circ g$. $L_{exis}$ will be noted as $x$ and $L_{turbines}$ as $y$.

$$\text{Let us define } f \text{ as: } f(X) = 10\log(X), \quad X \in \mathbb{R}^+ \tag{Equation 36}$$
$$\text{and } g \text{ as: } g(x,y) = 10^{\frac{x}{10}} + 10^{\frac{y}{10}}, \quad x, y \in \mathbb{R} \tag{Equation 37}$$

We get:

$$\frac{\partial f}{\partial x}(x,y) = 10 \cdot \frac{\partial \left(\log g(x,y)\right)}{\partial x} = \frac{10}{g(x,y)} \frac{\partial g(x,y)}{\partial x} \tag{Equation 38}$$

And

$$\frac{\partial g(x,y)}{\partial x} = \frac{\partial \left(10^{\frac{x}{10}} + 10^{\frac{y}{10}}\right)}{\partial x} = \frac{\partial \left(10^{\frac{x}{10}}\right)}{\partial x} = \frac{\ln 10}{10} \cdot 10^{\frac{x}{10}} \tag{Equation 39}$$

So finally,

$$\frac{\partial f}{\partial x}(x,y) = \frac{\ln 10}{10^{\frac{x}{10}} + 10^{\frac{y}{10}}} \cdot 10^{\frac{x}{10}} \tag{Equation 40}$$

The same calculation leads to

$$\frac{\partial f}{\partial y}(x,y) = \frac{\ln 10}{10^{\frac{x}{10}} + 10^{\frac{y}{10}}} \cdot 10^{\frac{y}{10}} \tag{Equation 41}$$

So, we get:

$$U_{fg} = \sqrt{\left(\frac{\ln 10}{10^{\frac{x}{10}} + 10^{\frac{y}{10}}} \cdot 10^{\frac{x}{10}} U_x\right)^2 + \left(\frac{\ln 10}{10^{\frac{x}{10}} + 10^{\frac{y}{10}}} \cdot 10^{\frac{y}{10}} U_y\right)^2} \tag{Equation 42}$$
Simplifying, it finally gives:
\[ U_{f,g}(x,y) = \frac{\ln 10}{10^{x/10} + 10^{y/10}} \cdot \sqrt{10^{2x/10} U_x^2 + 10^{2y/10} U_y^2} \]  
(Equation 43)

Finally, emergence noise level is calculated with \( E = L_{Amb} - L_{exis} \) associated with the uncertainty:
\[ U_{Emer} = \sqrt{U_{amb}^2 + U_{exis}^2} \]  
(Equation 44)

From these equations, it is interesting to know the impact of each uncertainty (existing noise, supplier and simulation) on the final result. The uncertainty given by the supplier will not be changed and considered as being always the same, at a value of 1 dB. For both existing noise uncertainty and simulation uncertainty, sensitivity analyses are shown on figure 43 and 44.

Figure 43 Impact of existing noise uncertainty on the minimum emergence noise for given existing and turbine noise levels of 35 dB

Figure 44 Impact of existing noise uncertainty on the minimum emergence noise for given existing and turbine noise levels of respectively 30 dB and 40 dB
These diagrams show that the impact of the uncertainties of existing noise and turbine emission noise are different according to the sound levels. Obviously, increasing one of the uncertainties will increase the final uncertainty on the emergence noise level but in a different extent. In the case where existing noise is much higher than turbine emission noise (case not shown), it is clear that the simulation uncertainty will not have a significant impact since the emergence will be very small. Only the existing noise uncertainty will have a significant impact. However this impact is not relevant since the emergence would already be near zero and then not causing any issue. In the case of equivalent noise levels, uncertainties can play an interesting role in the result. For both existing and turbine noise emission levels at 35dB(A) at the microphone location, figure 43 shows the impact of each of them.

For an increase of 1dB(A) on the existing noise uncertainty, we can see an increase of between 0.6dB(A) and 1dB(A) on the emergence uncertainty. For the same noise levels and an increase of 1dB on the simulation uncertainty, we can see an increase of about 1dB(A) on the emergence uncertainty. At equivalent noise levels, the uncertainty on simulation is then more sensitive than the existing noise level one. Looking at the values on emergence uncertainty, it reaches 3dB (emergence threshold at night time) and thus not reliable anymore from values of 1dB and 2dB respectively on existing noise and simulation uncertainties. To get an emergence uncertainty below the emergence threshold allowed, existing noise should then be measured with less than 1dB of uncertainty and the simulation should be made with no more than 2dB uncertainty.

In the case of higher turbine noise emission level than existing noise level (most of the cases), the sensitivity changes. For an increase of 1dB on existing uncertainty, it is an increase of maximum 0.5dB(A) only on emergence uncertainty. And for an increase of 1dB on the simulation uncertainty, an increase of up to 1.6dB can be observed on the emergence uncertainty. The simulation precision then becomes much more significant than the existing noise measurement. Looking at the values of emergence uncertainties, they are greater than the previous case. To keep an emergence uncertainty value lower than the emergence value itself, simulation uncertainty has to be lower than 3dB(A). Since simulation plays an important role in this case, uncertainties are greater and always larger than the emergence threshold allowed at night of 3dB(A). It would then probably not be interesting to show the authorities a result with an uncertainty that high. It can give insights for internal company considerations but the maximum of 3dB(A) at night (and 5dB(A) during the day) should not be exceeded when presenting results for the administration.

6.3.1.3. Potential benefit

The objective of these results is to conclude on how to apply these uncertainties on results found at the development phase acoustic study. Using uncertainties that are greater than the threshold defined by the norm as described in the section 5.1.8 would not enable concluding on the conformity. As far as it is known today, the threshold defined by the norm to consider measurement valid is 3dB. So no more than 3dB uncertainty should be used in the results. This threshold is probably going to change when publishing the norm 31-114. Since it is the allowed uncertainty at the commissioning control, it is then proposed to use the same value as a maximum uncertainty at the development phase for presenting the results to the administration. In case the uncertainty value is greater than the emergence value itself but still below the norm proposal threshold of 3dB(A), the emergence value would then be used instead of the uncertainty value. It allows keeping emergence values above 0. More generally, it is proposed to use a final uncertainty given by 

\[ U_{\text{dev}} = \min \left(U_{\text{Emer}}; E; S \right) \]

with \( U_{\text{Emer}} \) the emergence uncertainty defined and calculated as explained in section 6.3.1.2, \( E \) the emergence value itself and \( S \) the threshold defined by the norm 31-114 (3dB today).
Applying this uncertainty \( U_{\text{dev}} \) on emergence results found at the development phase acoustic study will allow more optimistic scenarios which will also be more reliable since the uncertainty will also be used at the commissioning control in the coming years. If uncertainties are not interpreted today at the commissioning time because of the norm which is not finished, they will be used soon. This proposed method of considering uncertainties at the development phase can then help get more reliable curtailment plans while keeping a high project value. Moreover, using the minimum between the calculated uncertainty, the emergence value itself and the threshold defined by the norm is easy to justify to the administration and the investor that will check the studies. It will be relying on official and reliable data.

Even if it is not possible to estimate the potential benefit the developer would get using these uncertainties, it can have a great impact by reducing the estimation of shutdown time of wind turbines. The exact same calculation as for the topography can be used. The advantage here is to only curtail a wind turbine instead of shutting it down. As seen before, it would in this case represent a gain of 124 410€/year/turbine under the same hypotheses used in section 6.2.3.3. These few decibels uncertainty could then lead to more optimistic acoustic plans considering the uncertainty that will be used soon at the commissioning time and to greater project values and more viable business plans.

### 6.4. Final potential benefits

Even if saving estimations that have been made are based on approximations and assumptions, it is interesting to have a rough idea of what it represents altogether. Table 5 summarizes the potential benefits estimated in the section 6.

<table>
<thead>
<tr>
<th>Proposition</th>
<th>Benefit/year/turbine (in k€)</th>
<th>Benefit over 20 years/turbine (in k€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adapting time of measurement</td>
<td>24</td>
<td>480</td>
</tr>
<tr>
<td>Using topography</td>
<td>124</td>
<td>2 480</td>
</tr>
<tr>
<td>Using uncertainties</td>
<td>124</td>
<td>2 480</td>
</tr>
<tr>
<td>Total</td>
<td>272</td>
<td>5 440</td>
</tr>
</tbody>
</table>

We can fairly consider that ABO Wind is going to install at least the same amount of turbines that it has until now. We can also consider that the same proportion of new turbines will need acoustic curtailment. It means that the improvements proposed here can be used for the potential 26 new turbines (over 115) that would be installed in the next years. Considering this number, the improvements of acoustic model proposed here would potentially lead to a saving of 7 million of euro per year. Over a lifetime of 20 years, it would finally represent a saving of 141 million of euro.
Conclusion

The French energy and wind power context was first presented before describing one of the main issues faced by this renewable energy which is its noise emission. The origin of the noise and basic acoustic principles were showed. A literature review was conducted, presenting numerical optimization, trailing edge blades and curtailment strategies. An estimation of financial loss of 12 million euro was showed due to acoustic curtailment for the wind developer ABO Wind only for current wind farms in operation. The problematic of noise emission legislation and the norm defining methods for the acoustic campaign once the wind farm is running were explained. The need to get reliable acoustic models at the development phase was showed and improvements finally proposed.

It is proposed to create more communication between the environment consultant and the acoustic one in order to define more precisely the time of the measurements and get more reliable data. The interpolation method defined by the norm has been tested and showed slightly different results. The regression used so far should not be used anymore and only this new interpolation as tested in section 6.2.2. The topography of the field should also be taken into account when estimating noise emission from wind turbines. It will present more reliable results corresponding to more optimistic scenarios since the wind mast is usually at higher altitudes than the wind turbine locations. Finally, a semi-analytical study was done on uncertainties, showing the sensitivity of each of them on the emergence noise level. It is finally proposed to use the minimum between the calculated uncertainty as defined in section 6.3 and the threshold for valid data defined in the norm 31-114.

Other parameters will need to be studied and adapted to the final version of the norm that will be published. ABO Wind just hired an acoustician who is going to work specifically on this problematic, continuing the work started here. In particular, parameters for the acoustic simulation such as the wind direction will need to be assessed. Another problematic that wind developers are facing more often is the impact of existing wind farms on the development of new projects. Is the noise generated by the current wind farm part of the existing noise or not? Noise regulation does not give indication on this and wind developers are currently defining a guide of “good practices” based on previous experiences. This work is finally a base for more developed research on the acoustic impact of wind farms in France.
7. References


[34] Harvard University, class of Physical Sciences, *A summary of error propagation*, Fall 2007


Once acoustic studies have been conducted and results giving curtailment time is set, it is then used to realize energy estimation. It will determine the value of the project and its viability. The first step consists in calculating the energy in the wind from the most recent data obtained with the wind measurement mast installed on site. The power from the wind is given by:

\[ P(V) = \frac{1}{2} \rho AV^3 \]  
(Equation 36)

With A the surface considered, \( \rho \) the air density and \( V \) the wind velocity. The wind measurement mast gives the wind velocity, the wind direction and the time of measurement every ten minutes. Wind velocity is measured at different heights and the reported at hub height using the following formula:

\[ V_H = V_h \frac{\ln\left(\frac{H}{Z}\right)}{\ln\left(\frac{h}{Z}\right)} \]  
(Equation 37)

With \( H \) hub height, \( h \) the height where wind is measured and \( V_H, V_h \) the corresponding wind speeds. In order to get an estimation as precise as possible, the wind speed at hub height is used. From the wind measurement mast data, a Weibull distribution is usually plotted and used as a probability function reflecting the wind resource of the field. If we call \( F \) the probability function representing frequency of each wind speed, the yearly wind energy can be calculated with an integral:

\[ E = 8760 \int_{v=0}^{v=25} F(v) \cdot P(v) \, dv \]  
(Equation 38)

With \( v \) the wind speed. We obviously know that \( \int_{v=0}^{v=25} F(v) \, dv = 1 \) because wind speeds only vary between 0 and 25m/s so it represents all the possible range of values. Given that the probability function \( F \) is discrete, it can then be calculated as a sum:

\[ E = 8760 \cdot \sum_{i=0}^{v=25} F(v) \cdot P(v) \]  
(Equation 39)

This represents the maximum energy available in the wind. But wind turbines cannot extract all of it. Instead of using the wind power showed before, \( P(v) \) is replaced by the function given by the turbine supplier (usually shown as a power curve). The sum calculation is then the same, using the swept area by the blades and the power given by the supplier for each wind speed. Given a turbine which was chosen before the acoustic study, energy calculation is done for day (7am-10pm) and night (10pm-7am) and shown for each wind speed. Data about curtailment power reduction are used in order to calculate the energy values for each noise reduction mode. A table such as table 5 is made. The third line represents the different noise reduction modes given by the supplier.
This is done for each turbine of the wind farm. Wind speed at hub height is used in the calculations. However, acoustic studies use a standardized wind speed calculated at 10m height. Then a factor calculated as followed is used to match the data:

$$f = \frac{\ln \left( \frac{H}{z_0} \right)}{\ln \left( \frac{h_{ref}}{z_0} \right)}$$  

(Equation 40)

With H hub height (100m here), $z_0$ the reference roughness (0.05m) and $h_{ref}$ the height reference (10m). Table 6 is made to get the match between speeds at hub height and at 10m.

**Table 7 Equivalent wind speed bins between v10m and v100m (last column)**

<table>
<thead>
<tr>
<th>v10 m</th>
<th>v100m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>4.3</td>
</tr>
<tr>
<td>4</td>
<td>5.7</td>
</tr>
<tr>
<td>5</td>
<td>7.2</td>
</tr>
<tr>
<td>6</td>
<td>8.6</td>
</tr>
<tr>
<td>7</td>
<td>10.0</td>
</tr>
<tr>
<td>8</td>
<td>11.5</td>
</tr>
<tr>
<td>9</td>
<td>12.9</td>
</tr>
<tr>
<td>10</td>
<td>14.3</td>
</tr>
<tr>
<td>11</td>
<td>15.8</td>
</tr>
</tbody>
</table>

57
Using the curtailment time tables given by the acoustic consultant, energy for each turbine at day and at night is calculated. An example of curtailment table is given by table 7. Standard means no curtailment, stop means the turbines is not running and the other terms represent noise reduction modes (curtailment modes). Each column (E1…) represents a turbine.

Table 8 Example of curtailment table defined by the acoustic consultant

<table>
<thead>
<tr>
<th>Wind speed (10 m agl)</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m/s</td>
<td>Standard</td>
<td>Standard</td>
<td>NRS A</td>
<td>Standard</td>
<td>NRS A</td>
<td>Standard</td>
</tr>
<tr>
<td>5 m/s</td>
<td>NRS C</td>
<td>100,7 dB(A)</td>
<td>NRS B</td>
<td>Nominal</td>
<td>Nominal</td>
<td>Stop</td>
</tr>
<tr>
<td>6 m/s</td>
<td>103,7 dB(A)</td>
<td>Standard</td>
<td>Stop</td>
<td>100,7 dB(A)</td>
<td>101,7 dB(A)</td>
<td>Stop</td>
</tr>
<tr>
<td>7 m/s</td>
<td>Standard</td>
<td>103,7 dB(A)</td>
<td>100,7 dB(A)</td>
<td>103,7 dB(A)</td>
<td>101,7 dB(A)</td>
<td>100,7 dB(A)</td>
</tr>
<tr>
<td>8 m/s</td>
<td>Standard</td>
<td>Standard</td>
<td>Standard</td>
<td>Standard</td>
<td>Standard</td>
<td>102,7 dB(A)</td>
</tr>
</tbody>
</table>

We calculated in table 5 the energy produced at each wind speed for each curtailment mode and for each turbine so only a sum is needed to find the corresponding energy for each curtailed turbine. This is done for each homogeneous class defined in the acoustic study. So usually wind direction which can define a specific homogeneous class is also added in the criteria of calculation (wind energy can depend on wind direction). The frequency of each direction is used to get final energy estimation for each turbine at each time (night and day) and each direction.

By summing up all these estimations, the final energy production of the wind farm is found. It is compared to the total energy estimation that would be given with no curtailment. The ratio gives the acoustic curtailment losses.