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Measurement of sound efficiency of trailing edge serrations (TES) on wind turbines in the Jura mountains.

Xavier Falourd, PRONA SA : x.falourd@prona.ch
Lukas Rohr, PRONA SA : l.rohr@prona.ch
Dominique Bollinger, HEIG-VD: dominique.bollinger@heig-vd.ch

Summary

ADEV Windkraft AG operates two wind turbines in St-Brais (Jura mountains in Switzerland). Given the particular topography and the proximity of the dwellings, the noise of wind turbines is clearly audible even if the immission limit values are respected. To overcome this effect, a retrofit of the blades has been done through the integration of trailing edge serrations (TES).

The main purpose of the study was to quantify the efficiency of the TES through the comparison on measurements done before and after the retrofit, measurements done at IEC61400-11: 2012 distances and at dwellings. The measurement protocol and all the data collected made it possible to extract reliable statistics for all the operating conditions of the wind turbines. The comparison of sound levels by wind speed class before and after installation of the trailing edge serrations (TES) shows that the reduction of the noise level of wind noise is between 2 dB and 4 dB at the emission for upper wind 6m/s at hub height. This paper presents the measurement campaign and the data analysis

1. Introduction

The ADEV company operates two wind turbines to St-Brais. Given the particular topography and the proximity of dwellings, the noise of the wind turbines is clearly audible even if the immission limits are respected. To compensate for this effect, a trailing edge serrations (TES) system was installed on each of the blades of the wind turbines at the end of the spring of 2017. The goal of this project is to control their acoustic efficiencies by measurements of control.

1.1 Principle of qualification of the wind turbine noise

Phases no.1 (spring 2017) and no.2 (fall 2017) were performed before and after the installation of TES and have permitted to collect acoustic, meteorological data and WT parameters of the two turbines so as to compare sound levels in bin classes at emission and at dwellings. Acoustic measurements were undergone near wind turbines (distance IEC61400-11:2012) and in two places of immission (dwellings at about 465 m and 565m of the nearest turbine) for two phases of about 25 days.
The comparison of noise levels by class of rpm before and after installation of the serrations of trailing (TES) at distances IEC61400-11 edge allows to quantify the reduction achieved near the wind turbines but also at dwellings (by extrapolation on the acoustic propagation and/or measurement).

Acoustic measurements at the immission locations also serve to qualify the audibility of the sound of the west wind turbine (WEA2) essentially during night time and weekend days.

2. Acoustic measurement protocol

Four sound level meters are used to perform simultaneous measurements of noise at the two emission locations (range IEC61400-11) and at two immission locations. Sound level meters are recoding continuous sound level LAeq, Leq in third octave bands (of 6.3 Hz to 20 kHz) as well as audio recordings. The positions of sound level meters for two measurement phases are similar with a precision of about two meters. A meteorological mast is located near the IEC61400-11 West point. The collected data, only for the second period, complete the wind turbine operational data sets.

The two sound level meters near WT are equipped with a secondary screen mounted on a rigid plate. Two sound level meters located at the immission points are placed on the ground and they are equipped with a secondary screen formed by a box open acoustic fabric-covered.

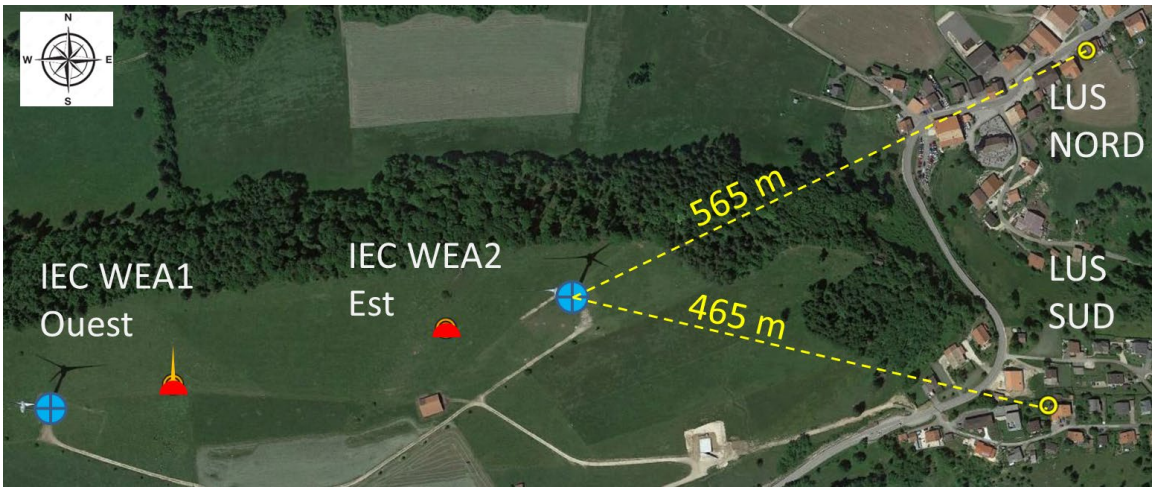

Figure 1: Locations of sound level meters and wind turbines WEA1 and WEA2

Figure 2: Pics of IEC61400-11 boards

Figure 3: Pics of microphone casing at immission points.

3. WT operational parameters

The two turbines operational data sets are documented for each phase of measurement through:

- Electric Power
- Rotation speed (rpm)
- Wind turbine orientation
- Wind speed at hub height

The temporal data of each parameter are delivered:

- phase no. 1 with a resolution of one minute,
- phase no. 2 with a resolution of 10 minutes.

3.1 Wind rose SCADA – Phase no.1

The figures below represent wind roses of each wind turbine for the first measurement period prior to installation of TES. It is remarkable that for this period the turbine WEA1 (West) is exposed to a wind stronger than the WEA2 (East) wind and the prevailing wind directions are somewhat different.

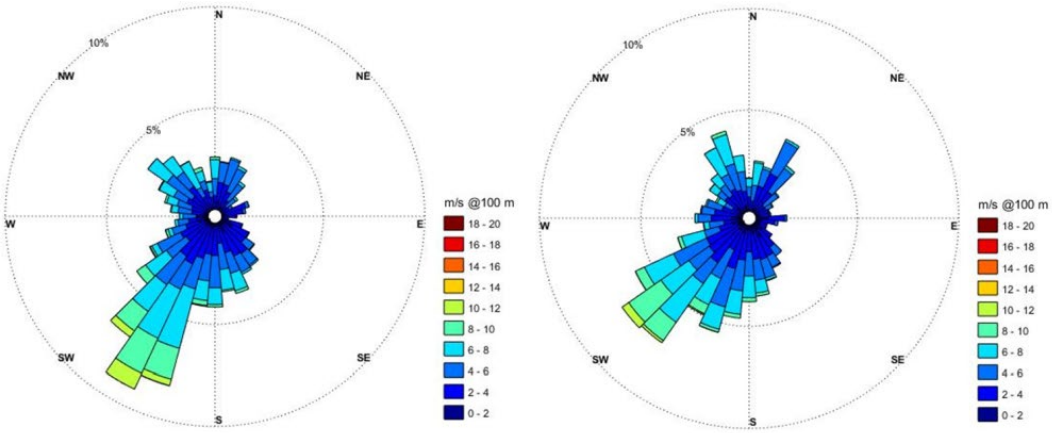

Figure 4: Wind roses phase no.1 (WT) - measurements of the wind at hub height. Left (West) WEA1, right WEA2 (East)

3.2 Wind rose SCADA – Phase no.2

The operational data sets of phase no.2 are delivered with a resolution of 10 minutes involving some interpolation of the data to have a resolution of one minute as for the first phase. The following figures present wind roses of each wind turbine for the second period after TES installation. It is remarkable that on this period the two wind roses are very similar with a predominance for winds from the Southwest.

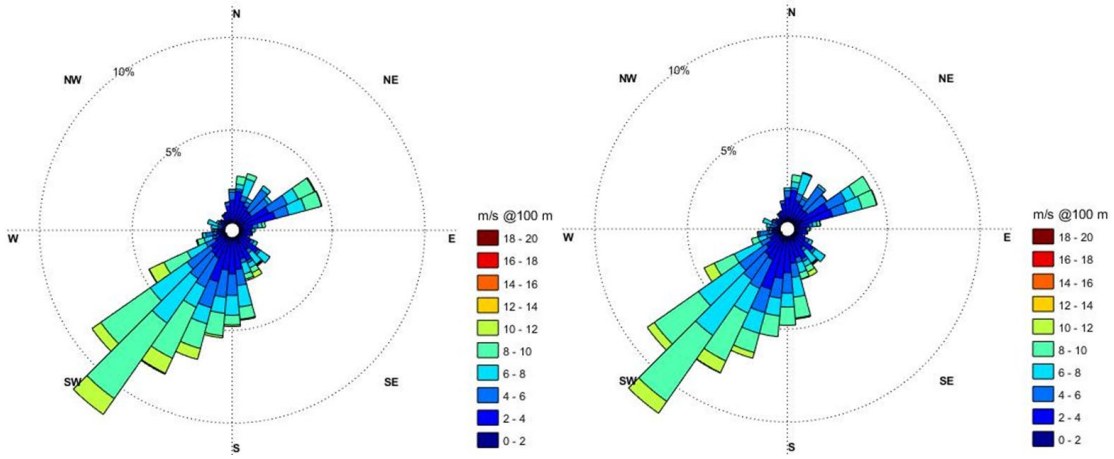

Figure 5: Wind roses phase no.2 (WT) - measurements of the wind at hub height (h = 78 m). Left (West) WEA1, right WEA2 (East)

3.3 WT statistics – Phase no.1

The following figure shows the two turbines operating statistics during the first phase of measurement. The night limitation performed on the wind turbine is (WEA2) is clearly distinguished when the wind speed is more than 8 m/s. There are two modes of power of the wind turbine is (WEA2) according to rotation speed (RPM).

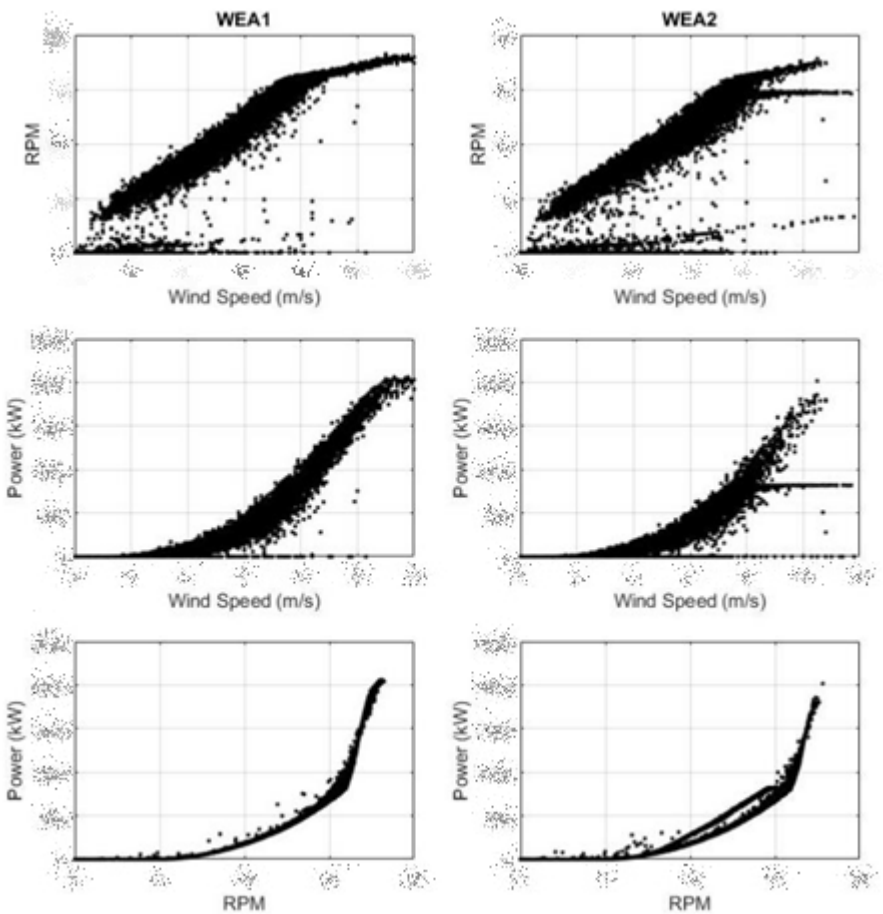

Figure 6: WT parameters - Phase no.1

3.4 WT statistics – Phase no.2

The following figure shows the two turbines operating statistics during the second phase of measurement. The night limitation being no more effective the statistics of the two turbines are very similar.

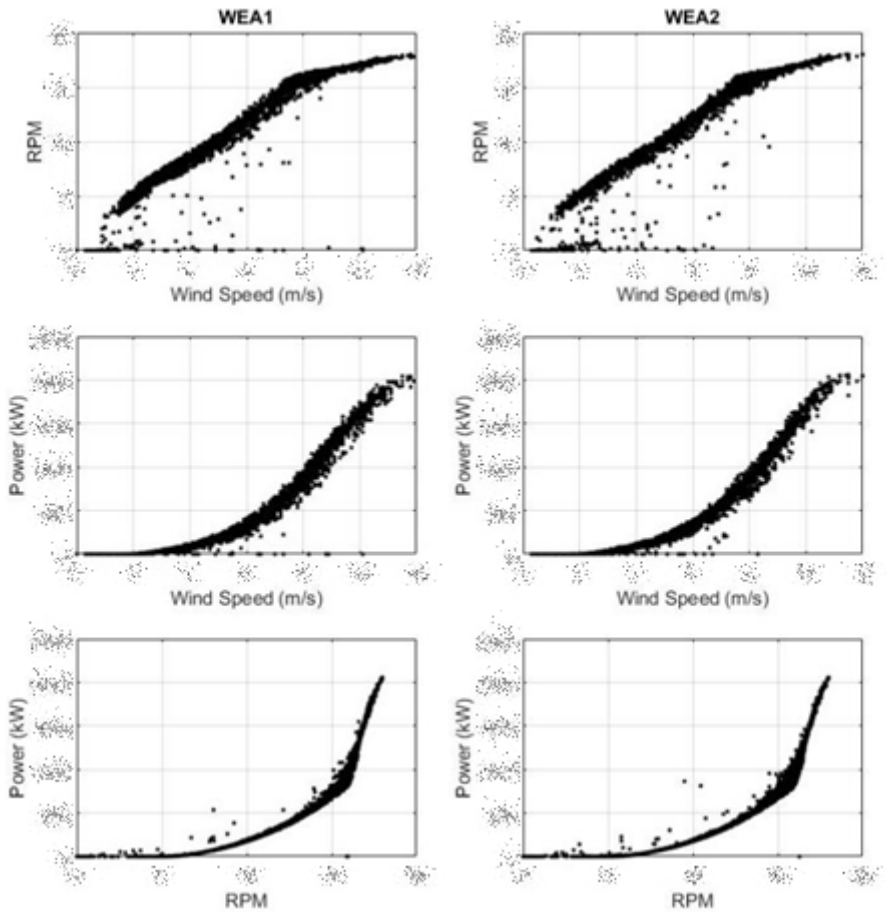

Figure 7: WT parameters - Phase no.2

4. Assessments by stop and go phase

The stop phases are designed to discriminate the wind noise of ambient noise at each point of measurement. According to the conditions of ambient noise, the sound of each turbine is quantifiable by differentiation of sound level LAeq or third octave bands.

Figure 8 is a report of a sequence alternating go-stop and go measurement of WEA1 (West) and WEA2 (East) wind turbines. This type of report indicates wind at hub height, RPM data for each wind turbine as well as noise data at the point of measurement.

All the reports of the stop and go tests indicate that the ambient noise on the wind farm site is low enough to allow significant acoustic measurements at distance IEC61400-11: 2012. On the set of measurements the emergence of wind noise on the ambient noise is located between 6dB approximately (wind 3 m/s, 6 rpm) and 25 about dB (wind 10 m/s, 18 rpm).

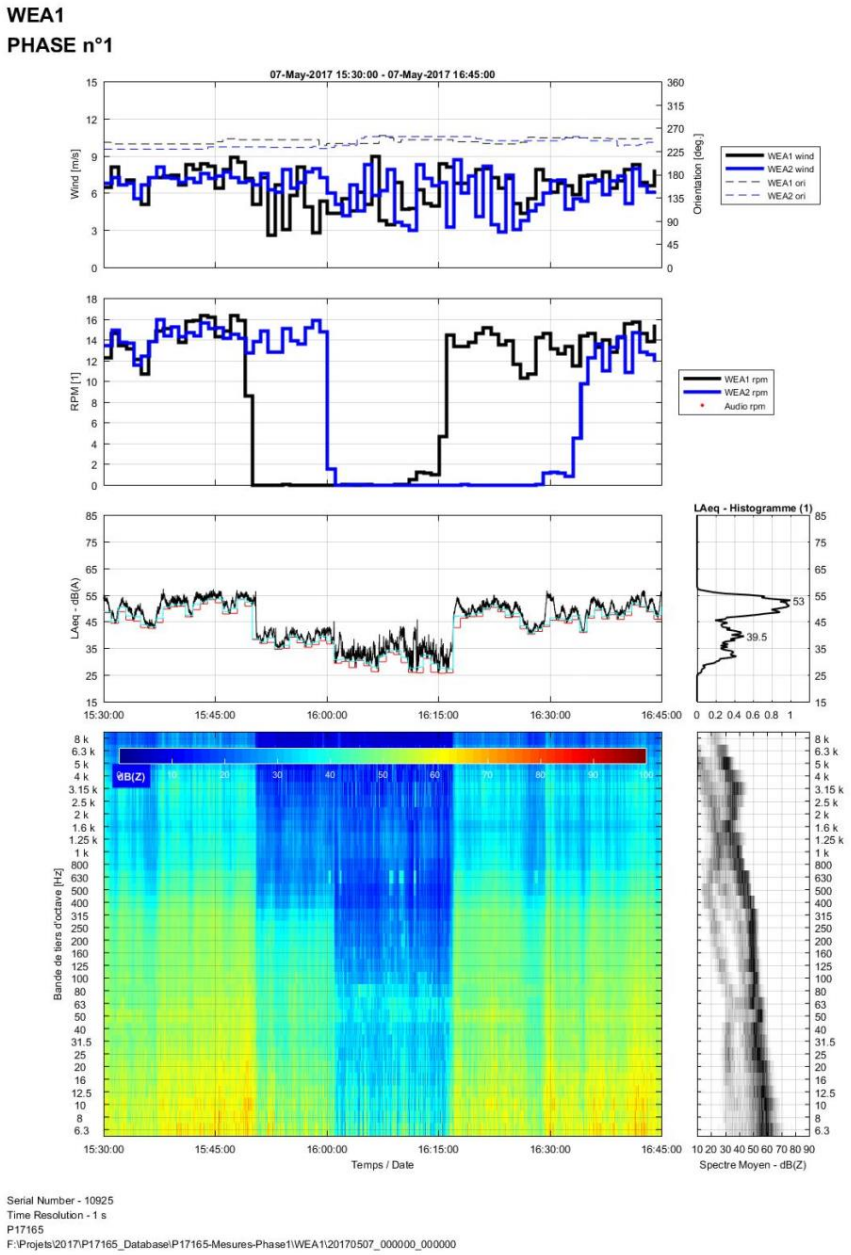

Figure 8: Report of measurement of wind noise at the IEC-WEA1 point to a sequence of stops (stops represented by the RPM curves to 0).

5. Noise statistics near the two wind turbines

Figure 9 and Figure 10 illustrate noise levels minimum LAeq (appointed Lmin in graphics) statistics for a period of observation of one minute depending on the speed of rotation (RPM) of the WEA1 (West) and WEA2 (East). The dispersion of the data is small, the average value per class of RPM allows to characterize the noise level by RPM class with good accuracy.

Note

Usually the sound levels are expressed relatively to wind at 10 m height. For the two phases (before and after TES) only operational data sets are available. Wind turbine noise being mainly composed of aerodynamic noise, the rotation speed of the rotor (RPM) is selected in place of the wind speed: wind turbine noise levels are almost a linear function of the rpm.

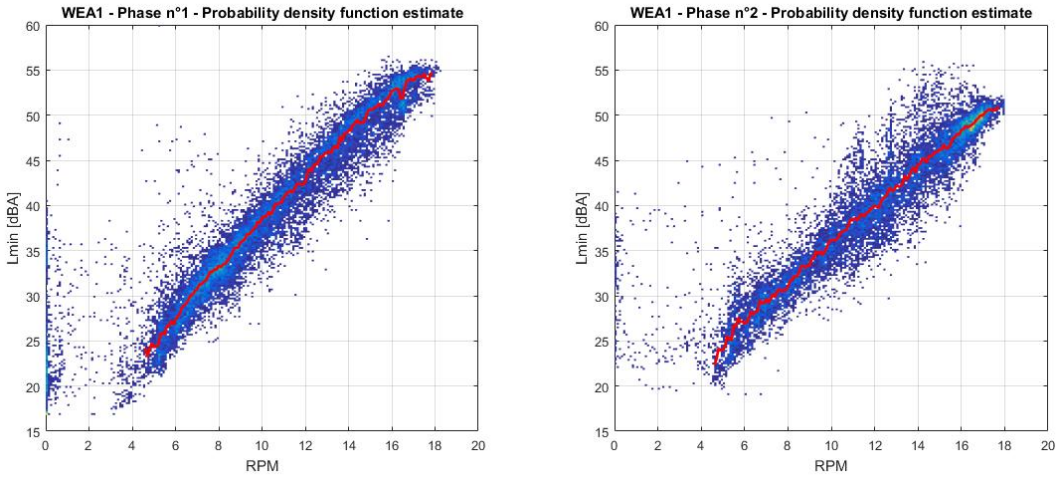

Figure 9: Raw statistics of the wind turbine WEA1 (West) - classified Acoustic measurements according to RPM data.

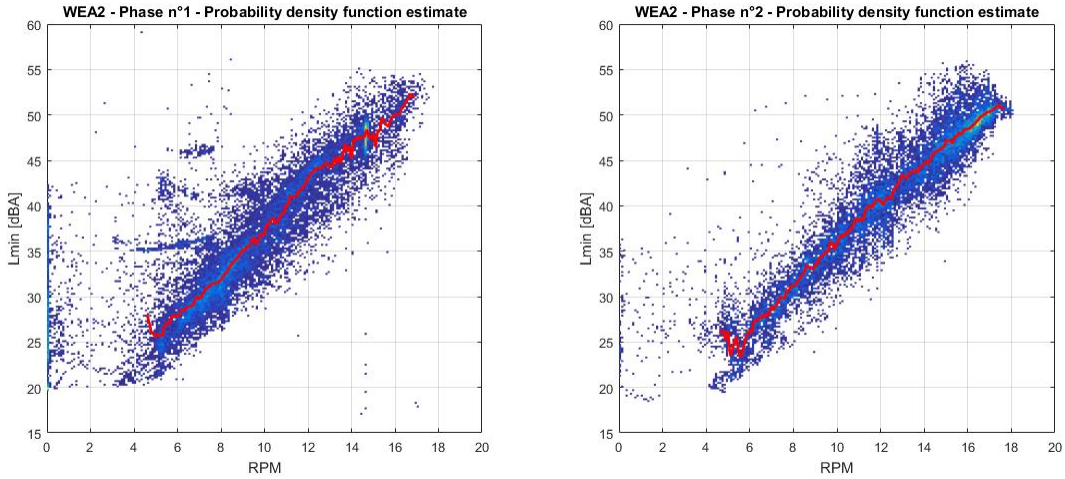

Figure 10: Raw statistics of the wind turbine WEA2 (East) - classified Acoustic measurements according to RPM data

The comparison of the mean values of the two turbines by phase noise is given in the Figure 11.

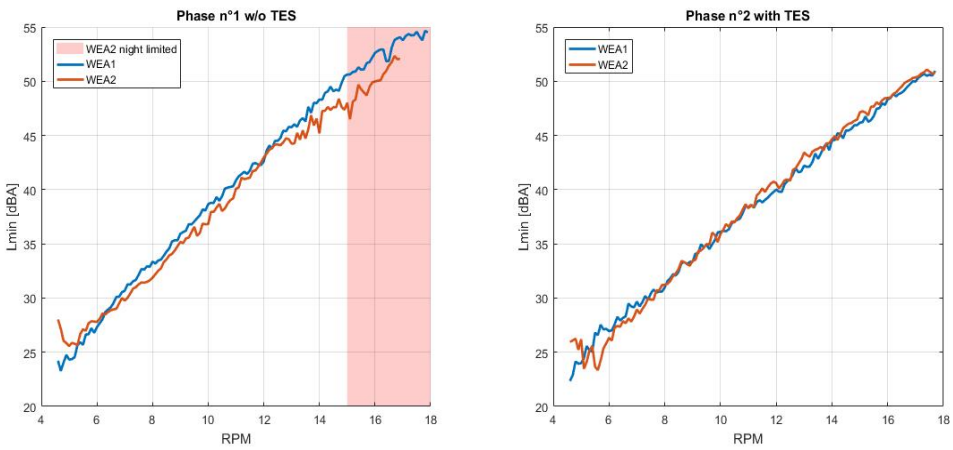

Figure 11: Comparison of noise from wind turbines WEA1 (West) and WEA2 (East) before and after TES installation.

For the phase no.1 despite a good similarity WEA1 and WEA2 curves are disjoint and can be explained by the fact that the wind rose is different for the two WT (speed and direction) and during periods of high wind speed, night limitations were applied to the turbine WEA2 influencing then the night statistics.

However for the phase no. 2, which offers roses of the same wind and without night limitation, the curves are considered the same. It validates the principle of measurement near the distances IEC61400-11 wind turbines: 2012.

6. Statistics on the efficiency of TES

The assessment of the efficiency of TES is performed by comparison of the average sound levels collected at distances IEC61400-11: 2012 the two phases of measurement. The following figures show the comparisons and the quantification of the efficiency of TES by speed of the rotor (RPM).

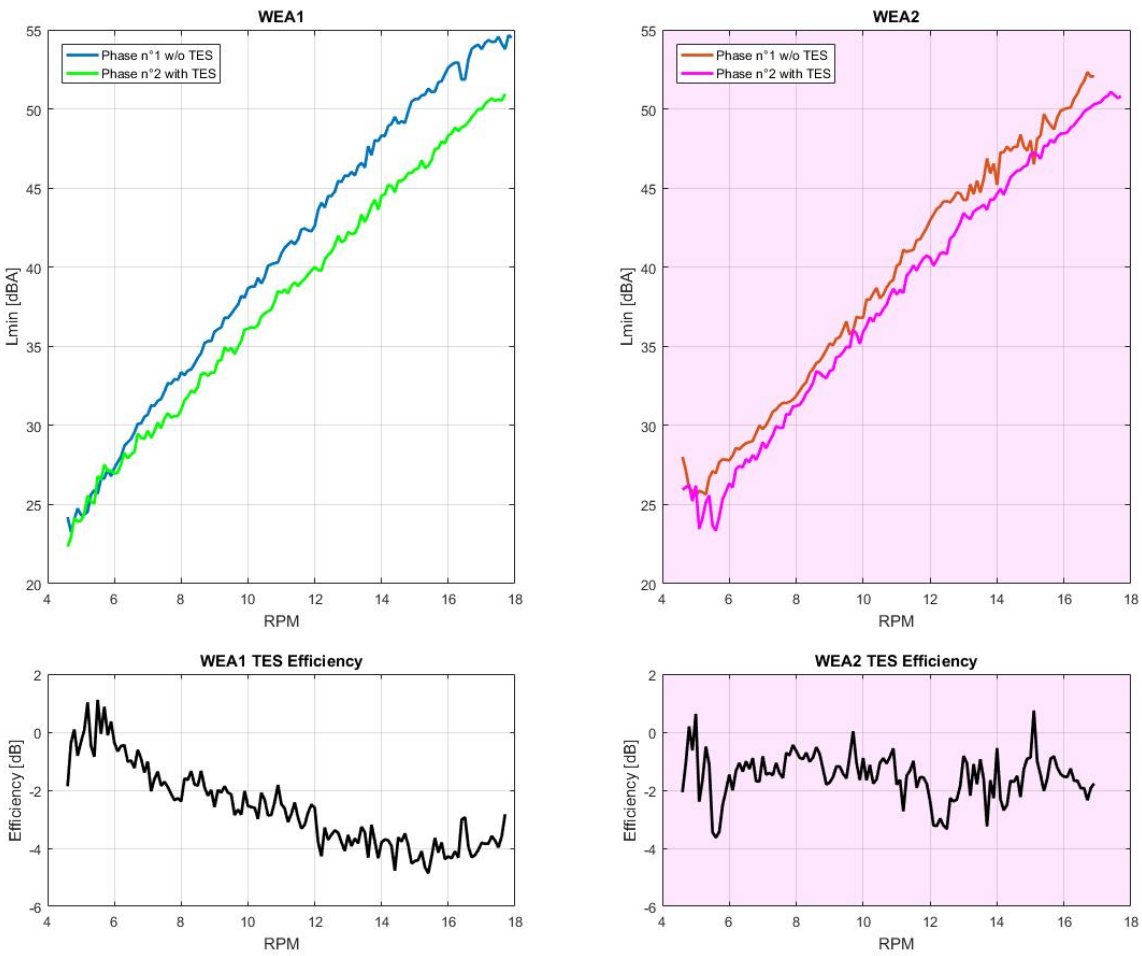

Figure 12: Average statistics of wind turbines WEA1 (West) and WEA2 (East) - top: comparison of noise levels before and after installation of TES: downstairs: statistical estimation of efficiencies. WEA1 is the reference for estimating turbine (no night clamping the first phase instead of WEA2).

For wind WEA1 (West), the measured efficiency offers a gradual reduction of the noise level between 0 dB and 4 dB according to the RPM. Under the assumption that the turbulence in exit of blades develop at high speed, efficiency of TES to reduce noise to airflow is greater at full speed than at low speeds.

For the wind WEA2 (East), measured efficiency offers a 2 dB of noise reduction on average but does not increase the efficiency according to the RPM. For the interpretation of these results, it is to consider that the wind turbine WEA2 (East) was subject to a night limitation during phase no.1 and the wind roses differ before and after the TES installation.

In conclusion, according to the terms of interpretation expressed previously, the two curves of assessment of efficiency of TES indicate a reduction in the noise level of at least 2 dB for the rotation speeds above 8 RPM. The results obtained near the wind turbine WEA1 (West) are the most reliable in terms of conditions of measurements (similarity of the wind roses).

7. Spectra and TES efficiency

In order to evaluate the influence of TES on the spectra of wind turbine noise, the comparison is carried out on a representative period during which the power of the wind turbine is maximum. In fact the database for statistical comparisons on the efficiency of TES to the immission by wind (speed, orientation) class is limited following the night limitation of the WEA2 turbine during phase no. 1. For each measurement phase, a period of 30 seconds is found during which the wind noise is audible to the immission locations.

Figure 13 and Figure 14 present in the third octave band spectra in the range 63 Hz - 4 kHz of wind noise measured at distances IEC61400-11 (emission) and immission locations. For both periods, measurements are corrupted by extraneous noise with significant influences on the spectral areas (pink areas).
The efficiency of TES is significant mostly in the frequency bands between 125 Hz and 1 kHz (bands of audibility to immission locations) and in the bands of frequencies above 1.6 kHz.

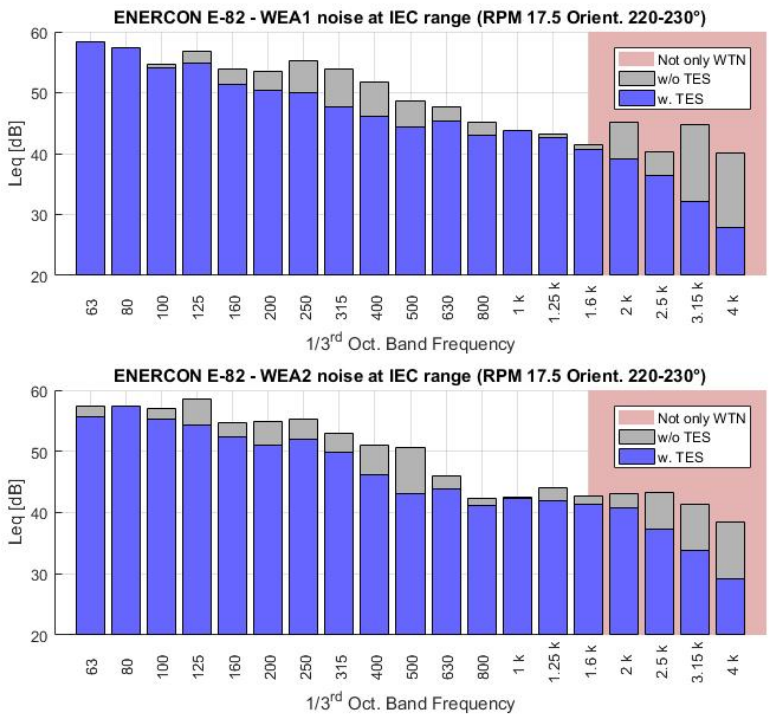

Figure 13: Spectra of IEC61400-11 distance before and after installation of TES

At dwellings the efficiency of TES is figured out for these same frequency bands indicating a reduction in noise levels.

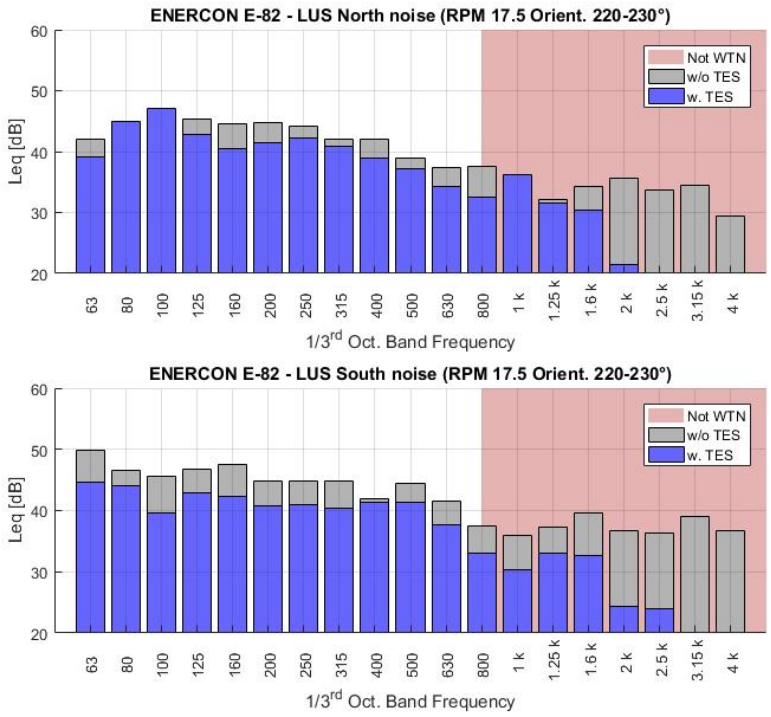

Figure 14: Spectra to read before and after installation of TES

The following table shows the noise levels LAeq (1 min) and L90 (L90 fractile index is the noise level LAeq met or exceeded 90% of the time, compared to the total duration of the measurement) corresponding to the emission and immission sites. For two wind measured at distances IEC61400-11, L90 levels indicate a reduction in the noise level of about 3 dB.

Sites / Sound Levels	**Phase n°1** RPM 17.5 Orientation 220-230°		**Phase n°2** RPM 17.5 Orientation 220-230°		**Différence**	
	LAeq dBA	**L90** dBA	**LAeq** dBA	**L90** dBA	**LAeq** dBA	**L90** dBA
IEC WEA2	57.6	55.3	53.7	52.1	3.9	**3.2**
IEC WEA1	57.1	55.1	53.6	52.1	3.5	**3**

Table 1: LAeq (1 min) and L90 sound levels for the two periods and for each measurement site.

8. Noise levels statistics near WT and at dwellings

Sound levels at the IEC61400 locations (WEA1, WEA2) and immissions sites (LUS North, LUS South) for the two phases are presented in the Figure 15 in their statistical forms according to the wind speed at hub height of the wind turbine WEA2 (West).

The average statistical noises at distance IEC61400-11 are represented by the red lines for the wind turbines WEA1 and WEA2. These last curves are then transposed forward to the immission locations: the calculation of wind noise at the immission locations is based on extrapolation of the noise measured at distances IEC61400-11 decreased in terms of geometric

divergence and losses by absorption according to the distance; the effects of soil and other spread effects due to field (relief) and barriers (buildings) are not factored by this modeling.

For every full curves (black and dotted) chart shows indicative values of wind turbine noise according to the data of the wind turbines. In the light of the statistical distributions of sound levels at the immission locations, it is remarkable that the observed minimum sound levels correspond to forecasts of sound levels calculated both statistically and by modeling.

The wind turbine WEA1 (West) participates only partially to the total wind turbine noise (less than 1 dB input) which is dominated by the nearest wind turbine WEA2 (East). Sound levels of wind turbine noise corresponding to the minimum values of the noise at immission locations; wind turbine noise is most likely still audible for winds higher than 6 m/s.

Although wind noise immission locations is mainly dominated by the WEA2 (East) wind turbine for which comparisons between the two phases are delicate due to the difference of the wind roses and the night limitations (only phase no.1), it can be concluded on the basis of a meticulous reading of these statistics that the efficiency of TES measured close to wind turbines can be transposed to the immission locations. Indeed the cross-reading of the statistics of the WEA1 and WEA2 turbines with modeling calculations allow to observe the reduction of wind noise at the immission locations.

As featured in noise reports at the immission (sound levels and spectra), wind noise is low emerging otherwise not present in the third octave bands above 800 Hz according to the ambient noise conditions. Thus, it would be interesting to express the same statistics for a sound level calculated in bands of frequencies from 20 Hz to 800 Hz.

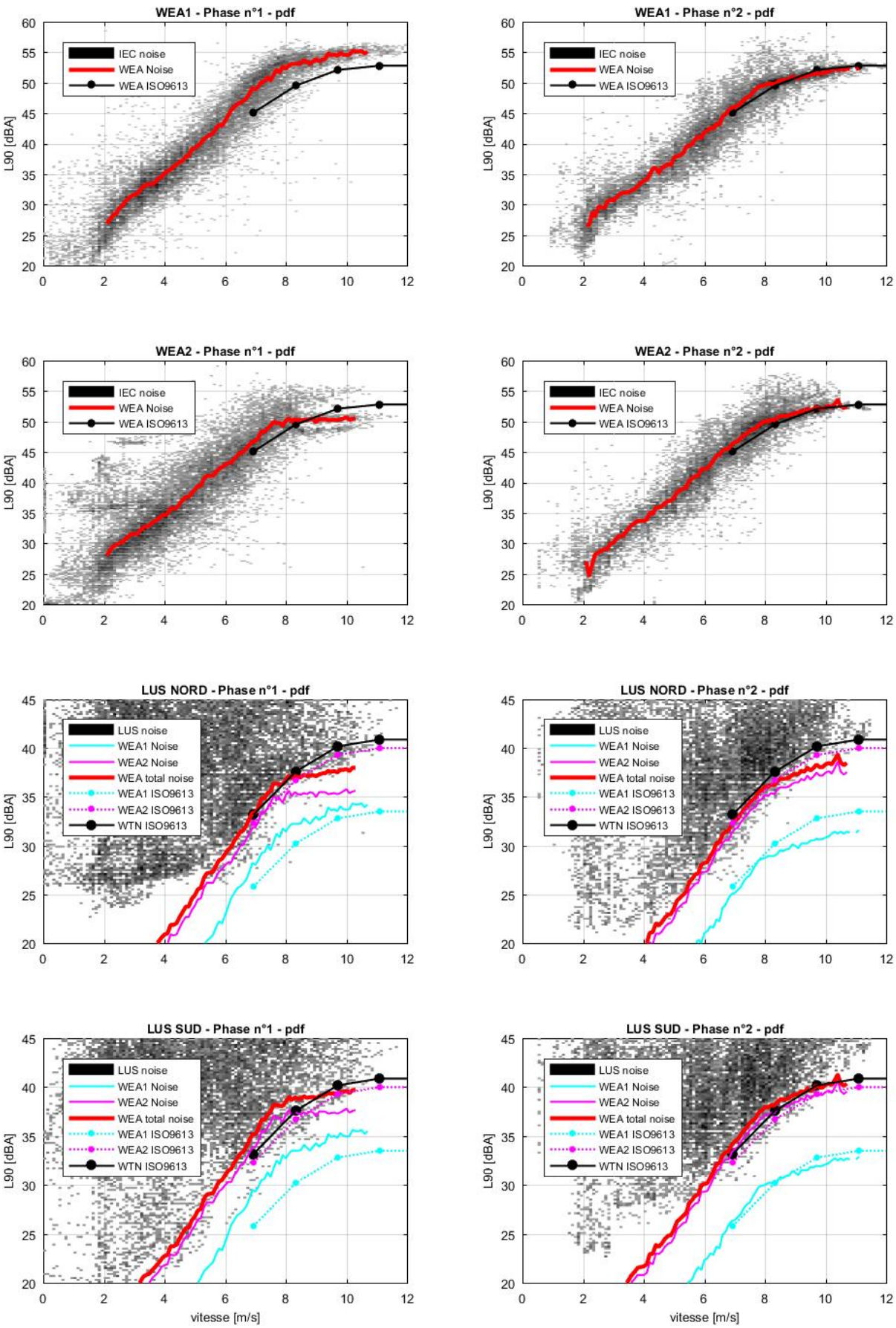

Figure 15: Statistics of sound levels L90 (1 minute). On the left, phase no. 1; right phase no. 2. Grey dots figures the raw noise data. Red curves are statistics of WTN. Black dot curves are approximation of the wind turbine noise according to ISO9613-2. The wind speed is measured at hub height

9. Remarks on the evaluation of audibility

The strong emergence of wind turbine noise on the ambient noise being permanent at distance IEC61400-11, the wind turbine noise (repeating audible pattern correlated with the rotation of the rotor) is clearly distinguished in sound recordings. The estimate of speed of rotation RPM of each wind turbine is achievable if based on a suitable data processing in strips of third octave with sufficient temporal resolution (here 125 ms). When operating the transformed of Fourier on specific bands of the sonogram in third octave bands, it is possible to express an instantaneous RPM with a resolution of about 3 seconds.

The following figure shows for a period of several days the extreme values of operational data (blue: maximum values, minimum values cyan) and the RPM values calculated from the audio analysis (in pink). For the speeds of the rotor at 3 rpm, the algorithm fails (lack of emergence of wind turbine noise). For speeds of rotation of the rotor higher at 3 rpm, estimates of the instantaneous rotation speed are therefore in good line as bounded by the extrema of the WT data. The characterization of the audibility of noise wind in a site, based on the hypothesis of the emergence of wind turbine noise on the ambiant noise is therefore achievable with this type of treatment.

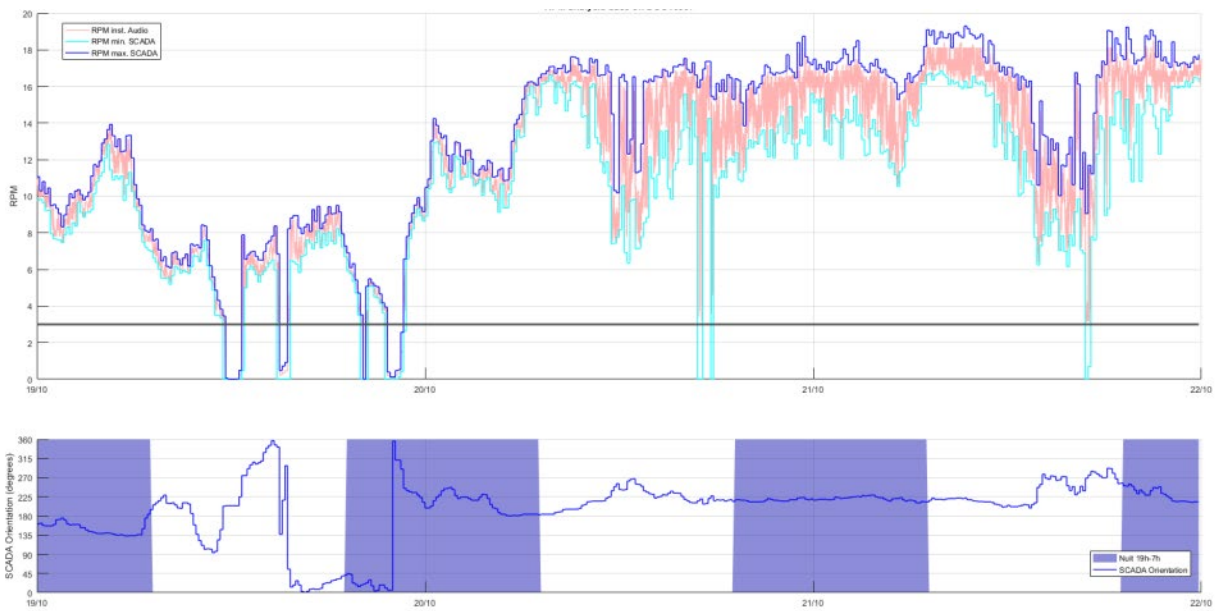

Figure 16: Assessment of the instant speed by audio analysis. In blue and cyan max and min of data values WT; in pink the instant RPM values from audio processing.

These same assessments of the speed of rotation of the rotor were conducted on immission sites. The following figure shows estimates of the RPM speed at the immission point LUS North of the phase no. 2. The calculated values of the instant RPM (in red) are present only when the wind turbine noise is detected. These "audibility" data are mainly found during night-time periods and weekend days i.e. the ambient noise is low.

This method, similar in principle to the one for the assessment of the amplitude modulations, could be studied more specifically for the qualification of the audibility phases of noise from wind turbines. The deepening of this method (robustness and precision) is not part of this project but remain of interest for the quantification of the audibility according to the swiss regulations.

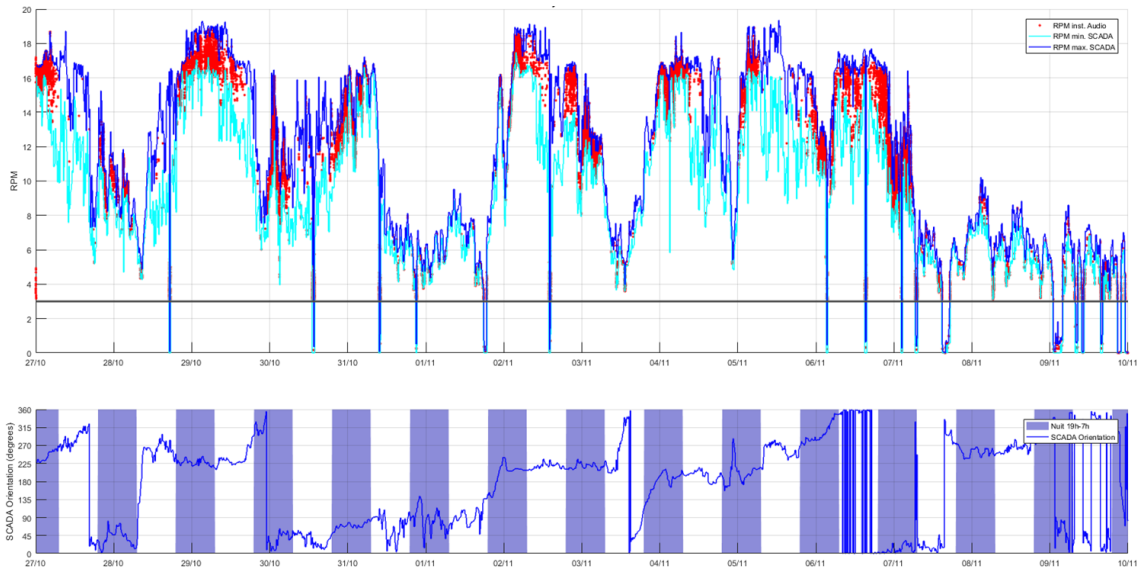

Figure 17: Evaluation of rotation speed RPM by audio analysis on Figueras North LUS - Phase data n ° 2

10. Conclusions

The main purpose of the study was to quantify the efficiency of TES, efficiency measured at distances IEC61400-11: 2012 near wind turbines. The measurement protocol and all of the data collected helped to extract reliable statistics to qualify wind turbine noise. The quantification of the efficiency of TES at immission locations has been estimated by extrapolation due to the ambient noise conditions and the night limitation (operated before the TES installation). Based on our statistical analyses and other listening to audio recordings, wind turbine noise was decreased by the TES which are effective in the audible band between 125 Hz and 1 kHz, frequency bands characteristic of wind turbine noise at mean and long distances (immission locations). Comparison of noise by rotation class (rpm) or wind speed class before and after installation of the trailing edge serrations (TES) shows that the reduction of the sound level of wind noise is between 2 dB and 4 dB near the wind turbine and about 2 to 3 dB at the immission for wind speed higher than 6 m/s or 12 rpm.

References

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