Fourth International Meeting on Wind Turbine Noise

Rome Italy 12-14 April 2011

Wind turbine noise in sheltered dwelling areas

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Abstract

The expansion of wind energy in Sweden is increasing as a response to the national target on carbon dioxide free energy. Many of the planned wind farms are situated in hilly terrain. Such sites have shown to be more sensitive to disturbances on wind turbine noise. This is believed to be caused by big differences in wind speed between the wind turbines and the noise sensitive areas as the wind turbines are often placed on higher ground for energy efficiency. The main reason for the increase in reported disturbances is that the wind turbine noise is more audible as the masking effect from wind induced noise is reduced due to low wind speed, especially at sheltered locations as housings in a valley were the wind turbines are located on the crest of the hill. The National Swedish Environment Protection Board has proposed that sites with big differences in wind speed between wind turbines and housings could compel a decreased guideline value. It is left to the project developer to show if that is the case, although no verified method to determine these sites is given. The main goal of this study is to develop such a method that can be used early in the planning process as an early adoption could lead to decreased development costs. Measurements of noise immission from wind turbines are performed at several sites in both the southern and northern parts of Sweden. At some of the sites disturbances has been reported believed to have been caused partly of the described phenomena. Based on the analysis and results suitable steps are discussed and a method presented. The results in this paper are part of a project financed by the Swedish Energy Agency.

Introduction

In Sweden many of the prospected wind farms are planned at locations with big variations in topography. At several existing wind farms situated at such locations disturbances of noise has been reported. The main reason is believed to be that the dwellings are located in sheltered areas were wind induced background noise is low compared to noise from the wind turbines, often placed at nearby hills, thus decreasing the masking effect on wind turbine noise. The National Swedish Environment Protection Board proposed that sites with big differences in wind speed between wind turbines and housings could compel a decreased guideline value. A wind speed ratio of at least 2:1 between wind speed at the wind turbines and the dwellings has been suggested as condition. This suggested condition has not been verified by measurements. The main goal of this study is to develop a verified method which can be adopted early in the planning process. This work has been partially financed by Energimyndigheten, the Swedish Energy Agency in project 32446-1, which is gratefully acknowledged.

Method

The first step is to perform measurements of sound and wind at several sites to find which factors are of importance for evaluation. Based on the identified factors a suitable verification method is discussed. The performed measurements should be carried out according to the recommended measurement standard in the Swedish guidelines for wind turbine noise. The recommended measurement standard is [1] a Swedish version of the International standard presented in [2].

The measurement procedure according to the standard is to measure the sound pressure level at 1.2-1.5 m height and wind at 10 m height at the immission point. Wind speed at the wind turbine is evaluated from produced power of the wind turbine and is scaled down to 10 m height at the reference condition, i.e. roughness length 0.05. Sound can be measured in free field or with the microphone mounted on the façade of a building using a standardized measurement board, a so called 6-dB measurement. Double wind screens are used to minimize the influence of wind induced sound at the microphone.

Suitable measurement sites for this project should follow the criteria that the wind turbines are placed on high altitude in hilly terrain and the immission point should be located in a supposed sheltered location. Measurements have been performed at three such locations. All sites have been anonymized in the presentation. For some of the sites there have been complaints on disturbances from wind turbine noise.

Measurements - Site 1

Site 1 is located in southwest of Sweden and the wind farm consist of 6 wind turbines in MW class. There have been complaints on noise from the wind turbines at a nearby dwelling, were the measurements are performed. Disturbances are most frequent for some wind directions when the dwelling is most likely to be sheltered by hilly terrain. The height difference between the dwelling and the wind turbines is at most 130 m. The calculated equivalent sound pressure level is far below the Swedish guideline value 40 dBA. A satellite picture of the site is presented in figure1. Downwind conditions according to the standard occurs for 150° ±45° wind direction were the nearest wind turbine, WTG_{ref}, is located 1200 m from the immission point.

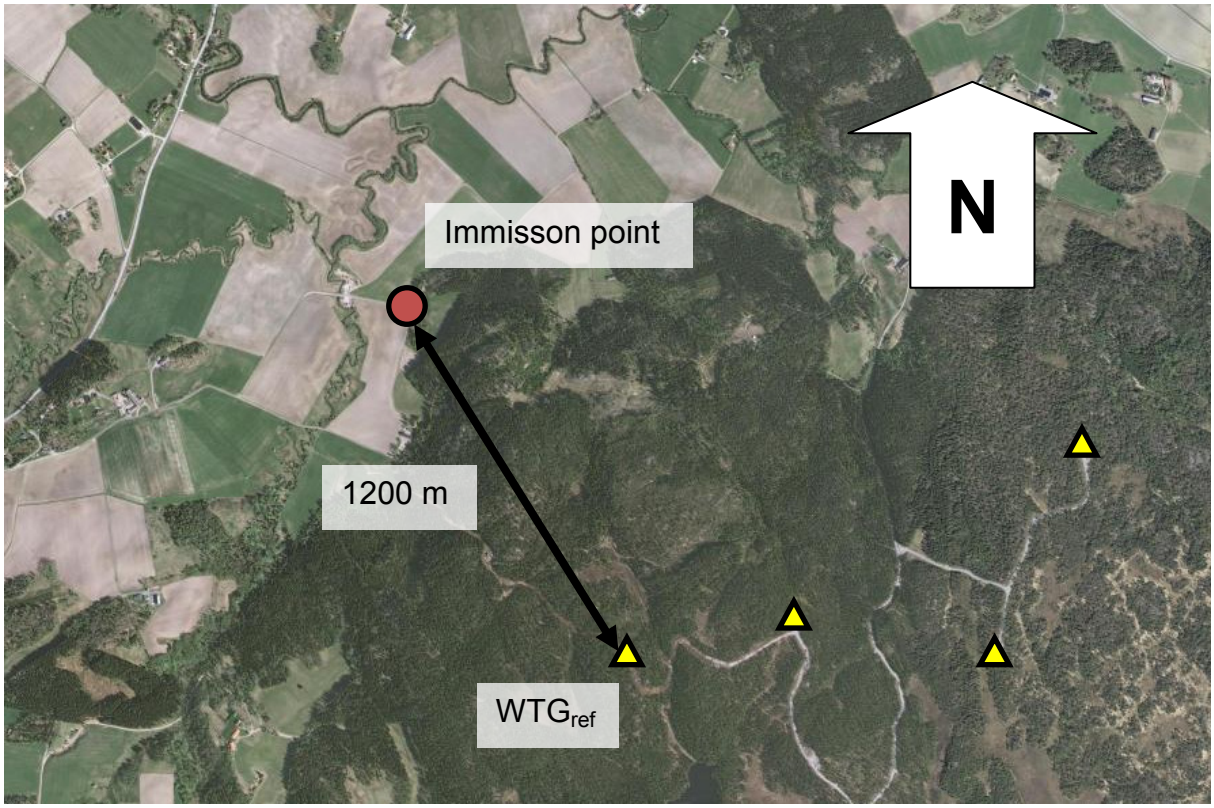

Figure 1. *Satellite picture of site 1 with the immission point, ●, and four of the wind turbines, ▲, marked. Nearest wind turbine,* WTG_{ref}*, at a distance of approx. 1200 m.*

Measurements are performed for a period of three weeks and all data has an interval time of 1 minute. The microphone is mounted on a standardized measurement board on a facade that faces the wind farm, all measured sound pressure levels are reduced with 6 dB. Data reduction have been performed. Only points with a wind speed of 6 m/s or higher, at 10 m height, at the nearest wind turbine, WTG_{ref}, were considered. Wind speed 6 m/s is chosen as it is for wind speeds above this that complaints are most likely to occur and any relations are more likely to be shown in the analysis. Wind speeds between 6-10 m/s are also those which should be analyzed according to [1]. Wind speed relative wind direction at the wind turbine, $WTG_{ref,}$ for the immission point and WTG_{ref} is presented in figure 2. The wind direction is equal to the hub direction of WTG_{ref}.

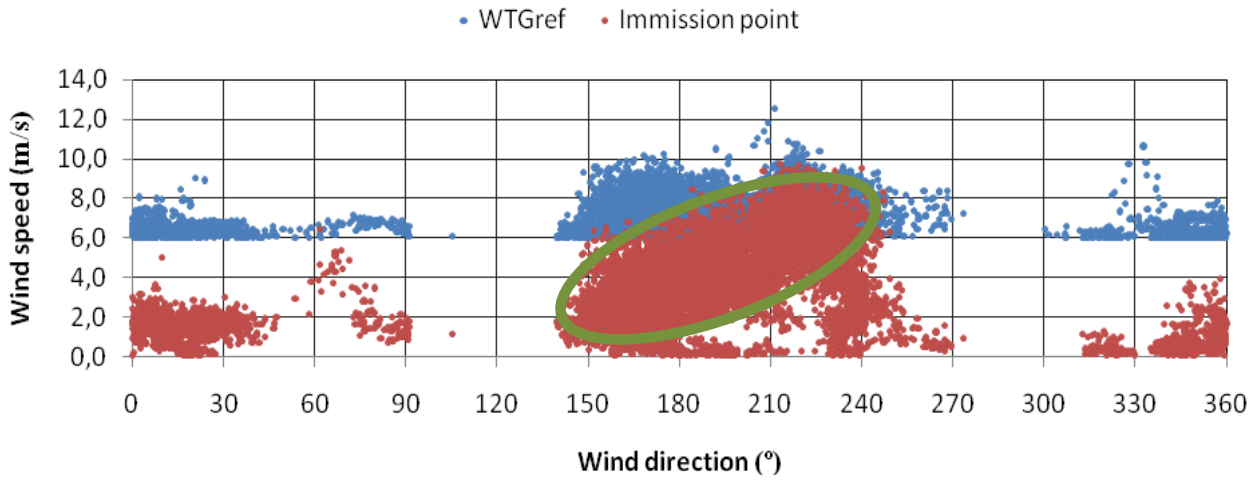

Figure 2. *Wind speed relative wind direction (hub direction) at the wind turbine for immission point and WTG_{ref}. Wind speed at WTG_{ref} over 6 m/s only.*

From figure 2 it is clear that the wind speed at the immission point is dependent on wind direction; see especially the marked area (green ellipse). The wind speed at the immission point is more equal to the wind speed at the wind turbine at a wind direction of approximately 200° to 240°. This means that the ratio between the wind speed at WTG_{ref} and immission point is lowest at a wind direction of approximately 200° to 240° although some values have a high ratio. In figure 1 it can be seen that these wind directions corresponds to reduced sheltered conditions for the dwelling area. In table 1, the wind speed ratio is presented for two wind directions 150°±5° (downwind) and 215°±5°given as the number of one minute values during the entire measurement period. A high ratio is more likely to cause audible noise from the wind turbines due to the reduced masking effect from wind induced noise. An interesting observation from the analysis is that large ratios, over 10:1, only seem to occur in the evening and night time primarily between 20:00-07:00. This is valid for all wind directions. This is also true to some extent for ratios down to 2:1 while the opposite holds true for ratios below 2:1 which are more frequent during day time.

Wind direction (WTG_{ref})	Ratio <2:1	Ratio ≥2:1	Average wind speed
150°±5° (downwind)	45	318	6.8 m/s
215°±5°	768	58	7.8 m/s

Table 1. *Example of ratio between wind speed at WTG_{ref} and wind speed at immission point for two wind directions with average wind speed for all analyzed values noted.*

Figure 3 shows the total equivalent sound pressure level at the immission point for the same conditions as in figure 2, that is, all values are above 6 m/s at WTG_{ref}. The presented values include both noise from the wind turbine and background noise from primarily wind induced vegetation noise. Trees and bushes are located near the immission point and also noise from a road at a distance of 900 m from the measurement point can be heard for some conditions. Noise from the wind turbines is clearly audible at time.

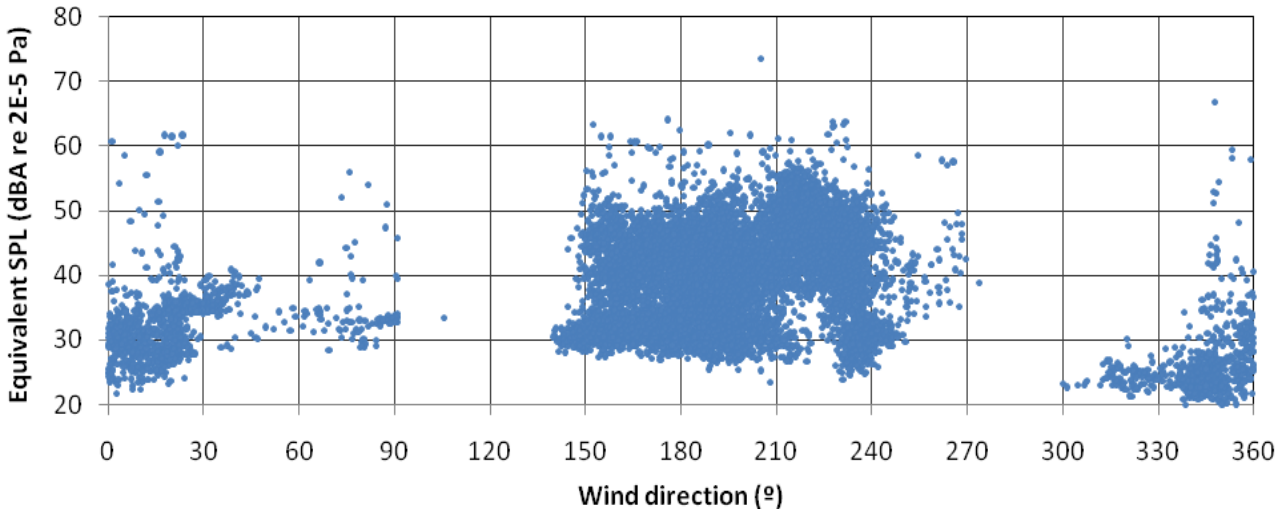

Figure 3. *Total equivalent sound pressure level at the immission point relative wind direction (hub direction) at WTG_{ref}. Wind speed at WTG_{ref} over 6 m/s only.*

The similarities with figure 2 can be seen which shows the relationship between wind speed at the immission point and the measured total sound pressure level. This is most likely due to the influence of wind induced noise were higher wind speed gives a higher total equivalent sound pressure level. Figure 4 shows analysis of the noise from the wind turbine according to method B in [1] which gives the value of the wind turbine noise including the background noise as no correction for background noise is performed. The analysis is done for downwind conditions 150° ±45° according to standard. As the measurement was unmanned and because of the number of data that is recorded during the measurement period, the one-minute intervals with high maximum sound pressure levels, L_{AFmax}>50 dBA, are cancelled.

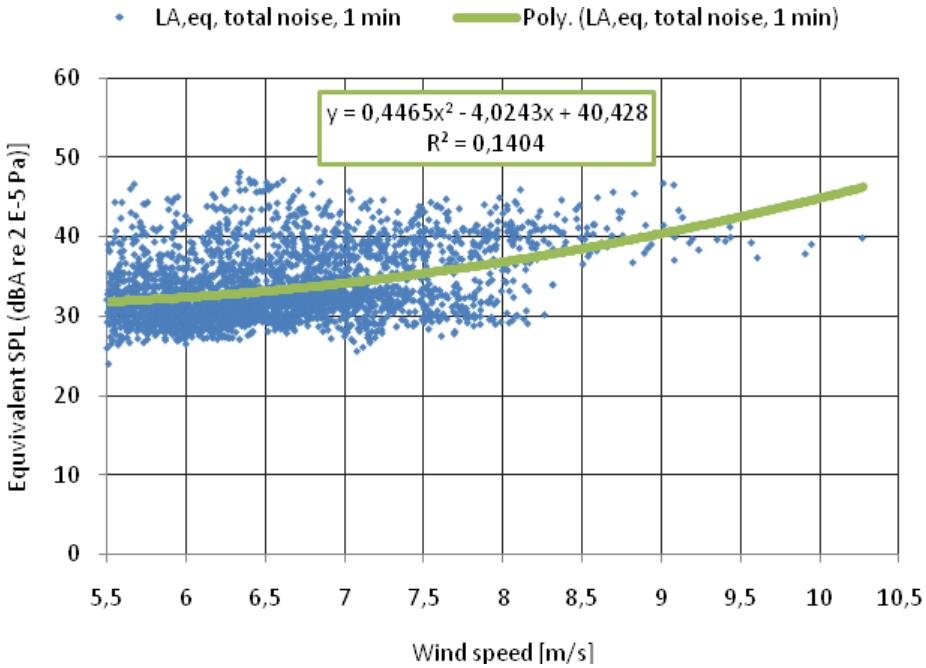

Figure 4. *Analysis according to method B in [1]. The sound pressure levels include background noise.*

Regression analysis according to standard gives an equivalent sound pressure level of 37 dBA at 8 m/s on 10 m height under reference conditions according to Swedish guidelines.It shall be noted that this is the total sound pressure level in the immission point and that the sound pressure level from the wind turbines is probably lower. The calculated value is 33 dBA.

Summary for site 1 is that for some wind directions the dwelling is more sheltered which could make the wind turbine noise more audible, although the guideline value is fulfilled. The wind speed ratio for downwind conditions are mostly over 2:1 which fulfill the conditions suggested by The National Swedish Environment Protection Board and thus could imply a reduced guideline value. Of importance is that the conditions are not fulfilled for all wind directions for example 215° according to table 1 which is also a more frequent wind direction during the measurement period. It seems that big differences in wind speed primarily occurs in the evening and night time.

Measurements - Site 2

Measurement site 2 is also located in southwest of Sweden. The wind farm consists of one MW wind turbine which is located 550 m from the selected immission point at a nearby assumed sheltered dwelling. Complaints on wind turbine noise have been reported although the wind farm produces noise below the guideline value in calculations. The height difference between the wind turbine base and the dwelling is 75 m, an incline of about 17%. A photo from the tower base is presented in figure 5. The microphone is mounted on a facade facing the wind turbine and a 10 m measurement mast for meteorology is placed nearby. All measurement values has

an interval time of 10 minutes and the measurement period is one month. Downwind conditions occurs for wind direction 270°±45°.

Figure 5. *Picture from tower base showing the nearby terrain.*

Wind speed relative wind direction at the wind turbine for the immission point and wind turbine is analyzed and presented in figure 6. Only values with wind speed above 6 m/s are shown with explanation as previously. Wind direction is equal to hub direction for the wind turbine.

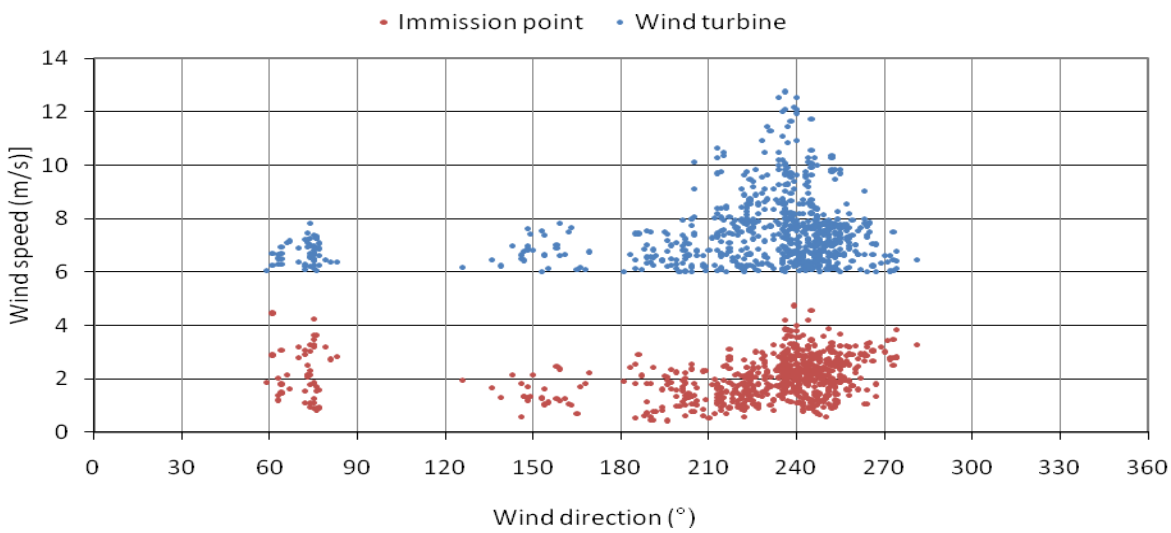

Figure 6. *Wind speed relative wind direction (hub direction) at the wind turbine for immission point and wind turbine. Wind speed at wind turbine over 6 m/s only.*

Big differences between wind speed at the wind turbine and immission point can be observed. The largest wind speed ratio can be seen for wind directions at the wind turbine of about 200°-250°, thus fullfilling downwind conditions. This can be partly explained by looking at the topography of the site which is shown in figure 7. For these wind directions the wind blows almost at right angles to the hills crest which would imply for good sheltered conditions at the dwelling.

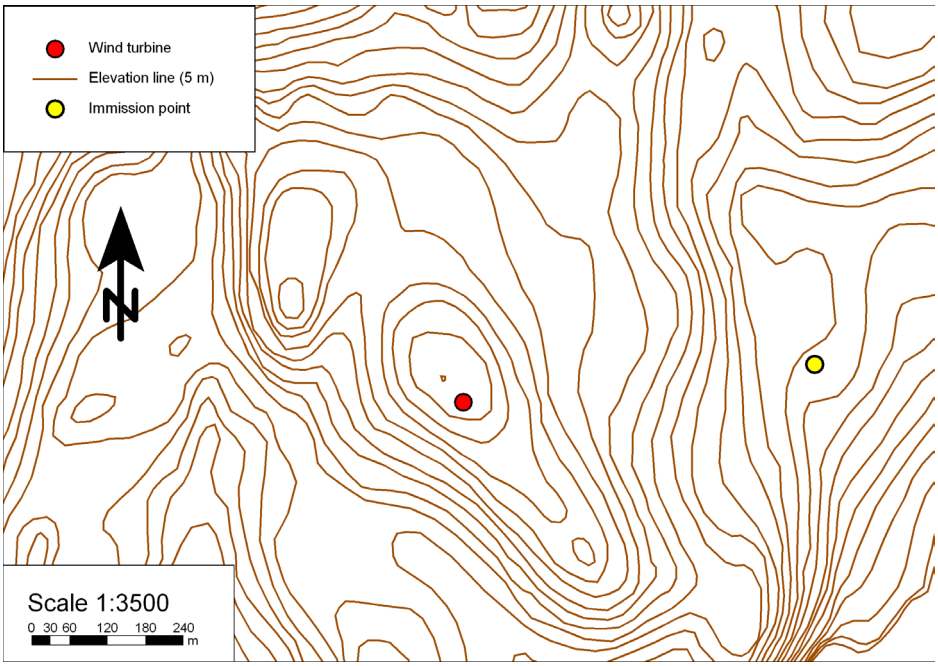

Figure 7. *Topography of the site with the wind turbine and immission point marked.*

The wind speed ratio is above 2:1 for almost all measurement values, wind speeds above 6 m/s, as presented in table 2. As for site 1 a big difference in wind speed primarily occurs in the evening and night time in this case approximately between 22-06.

Wind direction (Wind turbine)	Ratio <2:1	Ratio ≥2:1	Average wind speed
All directions	17	656	7.5 m/s

Table 1. *Wind speed ratio between wind turbine and immission point for all wind directions at the wind turbine with average wind speed for all analyzed values noted.*

Total equivalent sound pressure level versus wind direction at the wind turbine for the whole measurement period is given in figure 8, for wind speeds at the wind turbine above 6 m/s. Sound from the wind turbine is clearly audible in the immission point for some conditions as well as wind induced vegetation noise from nearby trees and bushes.

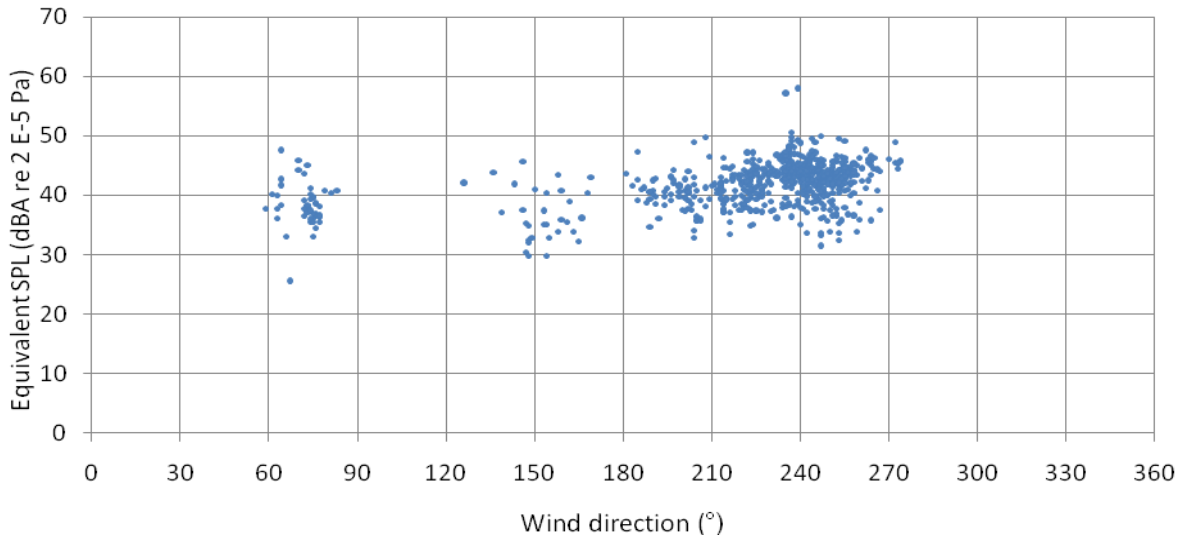

Figure 8. *Total equivalent sound pressure level at the immission point relative wind direction (hub direction) at the wind turbine. Wind speed at wind turbine over 6 m/s only. The sound pressure levels include background noise.*

The same similarities as for site 1 can be seen comparing the total noise level and wind speed at the immission point in figure 7. A majority of the measurement values exceds 40 dBA probably due to wind induced vegetation noise and other temporary noise sources in the nearby surroundings. Analysis according to method B in [1] gives the result in figure 9. Data reduction is performed and all measurement values with a maximum sound pressure level of L_{AFmax}=48 dBA are eliminated from the presentation. The result represents downwind conditions according to the standard with a wind direction of 270°±45°. Due to small amount of data, values down to 4 m/s are included in the regression analysis.

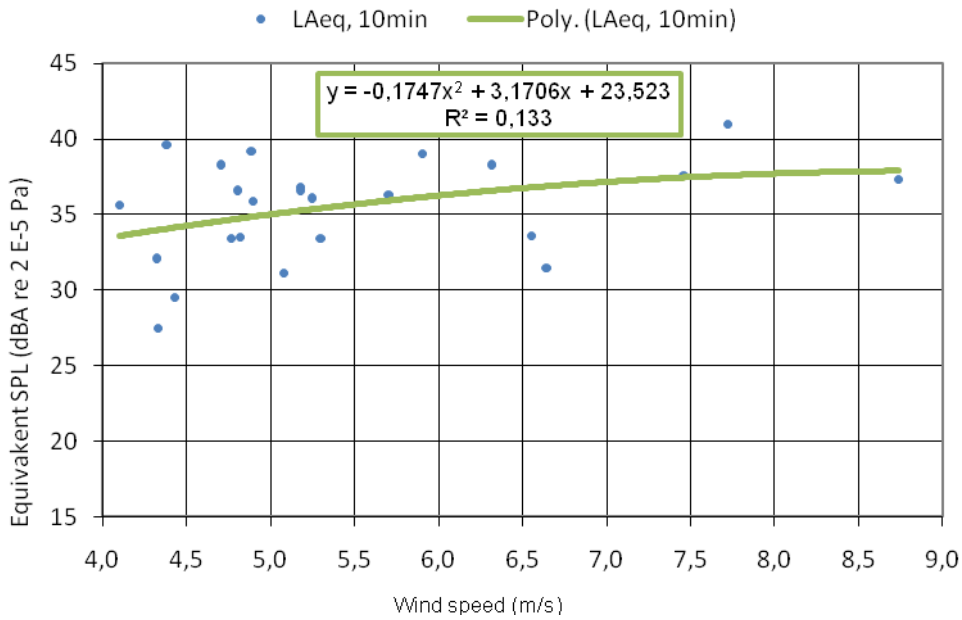

Figure 9. *Analysis according to method B in [1]*

The equivalent sound pressure level at 8 m/s is extracted through the second order polynomial as 38 dBA which represents the total sound level in the immission point. This is close to the calculated value.

Conclusions for site 2 concur with those for site 1 with the difference that the wind speed ratio is 2:1 or more for almost all measured data pairs of wind speed. This would meet the proposed conditions for a sheltered dwelling area which could lead to a more audible wind turbine noise causing increased disturbance. A big wind speed ratio is most likely to occur in the evening and night time.

Measurements - Site 3

Located in northern Sweden site 3 consists of 5 wind turbines in MW class. The immission point is not located near a dwelling, it has been chosen for the anticipated sheltered conditions. The calculated value in the immission point is 42 dBA and the distance from the nearest wind turbine is 550 m with a height difference from turbine base of 110 m, for topography and measurement points see figure 10. Downwind condition according to the standard occurs for wind direction 260°±45°.

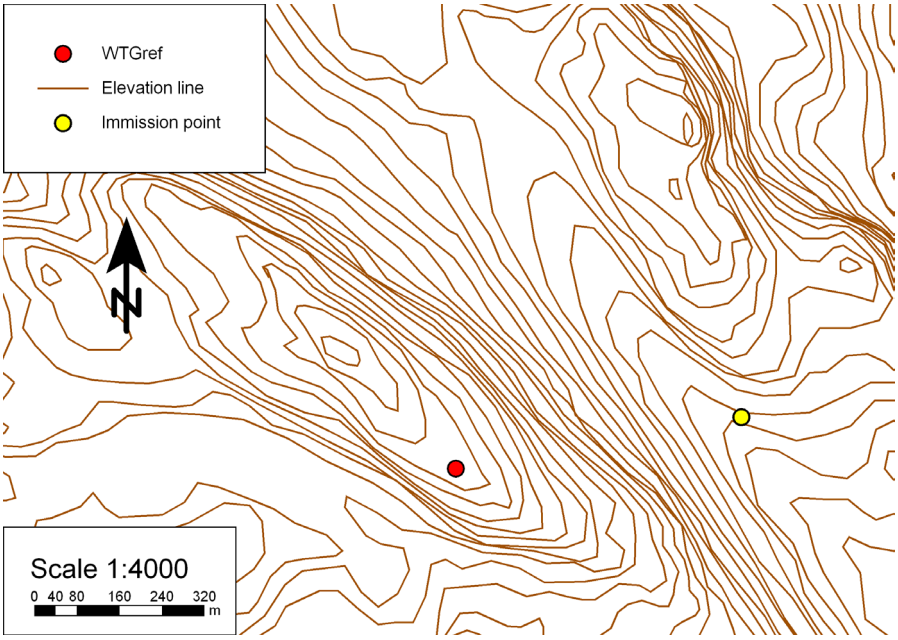

Figure 10. *Topography of the site with the nearest wind turbine, WTG_{ref}, and immission point marked.*

Measurement interval is 10 minutes for all data and the measurement was performed during 6 hours in night time. The microphone was placed on a tripod 1.5 m above ground with a 10 m mast for meteorology placed nearby. A big road with sporadic traffic during night time is located about 600 m from the immission point, its influence on the result is minimal. Figure 11 shows the wind speed at WTG_{ref} and immission point relative wind direction (hub direction) at WTG_{ref}. Reference conditions, roughness length 0.05 m, are not applied in the analysis instead roughness length 0.3 m is used which meet the requirements in the standard when the measurement was performed. With roughness length 0.05 m the wind speed at the wind turbine would be a little bit higher.

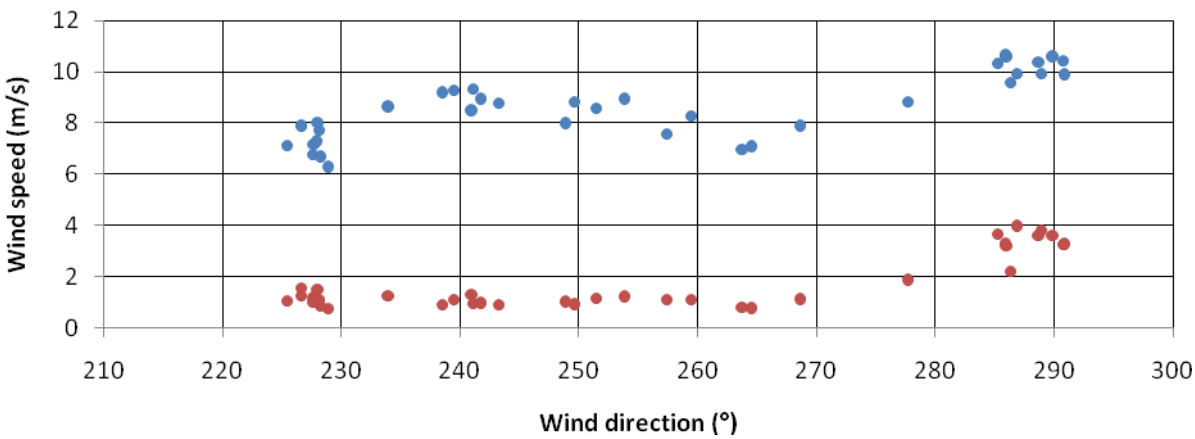

Figure 11. *Wind speed relative wind direction (hub direction) at the wind turbine for immission point and WTG_{ref}.*

When the wind turns to the north during the measurement the wind speed at the immission point is enhanced . Looking at the topography in figure 10 this could probably be explained by the decreased sheltering effect on the wind by the crest situatued to the west of the immission point, the wind can blow more freely down to the valley and the immission point. However, it shall also be noted that the wind speed at the wind turbines has increased as well. For wind directions below 270° no wind induced background sound can be heard, but for wind speeds of 3-4 m/s the influence of the wind induced background noise on the total noise is extensive. This shows that although the wind speed ratio is larger than 2:1 for all measured data pairs the wind induced background noise can for some cases be clearly audible and partly mask the wind turbine noise. The total equivalent sound pressure level is shown in figure 12.

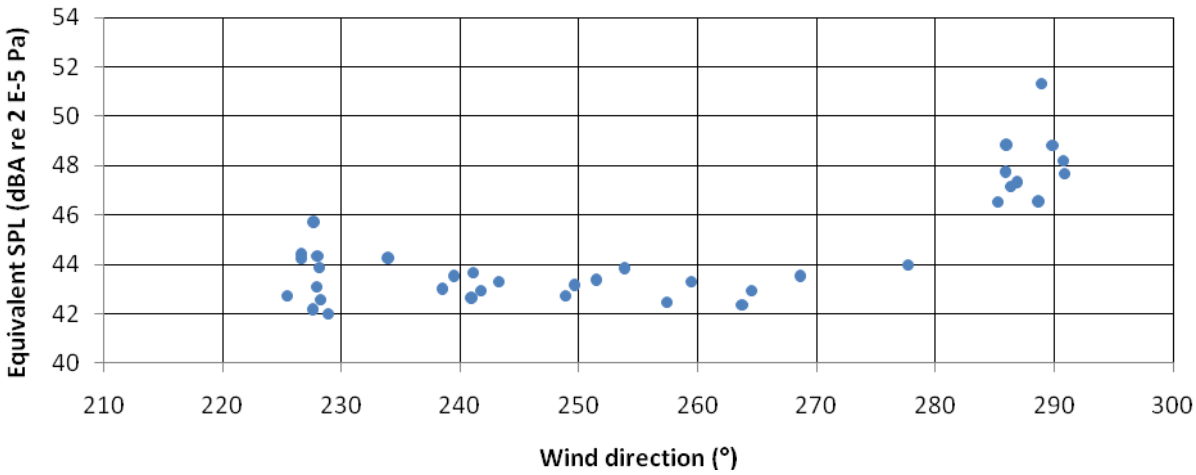

Figure 12. *Total equivalent sound pressure level at the immission point relative wind direction (hub direction) at* WTG_{ref}.

Influence by the wind induced vegetation noise can be seen in figure 12 for wind directions above 280°, the total level is raised approximately 5 dBA and the wind turbine noise is partly masked. The objective experience reported by the measurement personel was that the noise was less disturbing than with lower background noise. Figure 13 shows the analysis according to method B in [1], only values with a minimum influence by the background noise are used in the analysis.

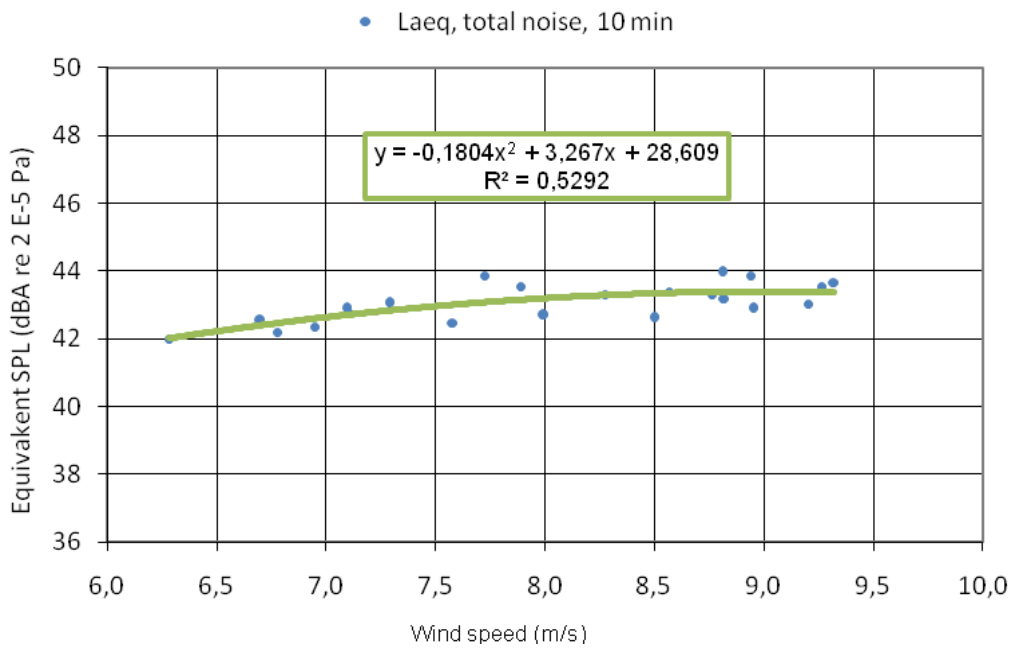

Figure 9. *Analysis according to method B in [1]*

Regression analysis gives the equivalent sound pressure level at 8 m/s as 43 dBA which is close to the calculated value. The measured value has minimum influence by the background noise.

Site 3 is a good example, which shows that the sheltering effect in many cases can be dependent on wind direction. Although the wind speed ratio is greater than 2:1 for all data pairs of wind speed the background noise is also dominant for some wind directions. As the measurements are performed for a limited period of time the statistical accuracy can not be guaranteed. It shall also be noted that wind speed at the wind turbine is raised during the measurement which could maybe explain the raise of wind speed at the immission point.

Discussion

The presented results show that it is not easy to establish a method that is valid for all cases. Four suggestions of an evaluation method based on the experience in this study are presented below.

1. Measurement of wind speed at the wind turbine and dwellings were also noise is measured.
2. Measurement of only wind speed or only noise.
3. Study differences of heights in the topography at the planned site and compare with known cases of sheltered areas.
4. Calculate wind speed in the microclimate based on detailed wind analysis.

Method 1 and 2 is probably the most accurate but could lead to extensive measurement programs and also bring halt to the planning process and are probably also the most expensive. Should measurements for example be carried out at all nearby dwellings or just a few? If measurements are going to be performed early in the planning process maybe a wind speed dependent guideline value would be better, as for example used in United Kingdom and in France.

Method 3 needs measurements at more locations for statistical certainty and maybe a class division for different topography. Could be suitable for mapping of big areas using inclination between the wind turbines and dwellings but needs good altitude data.

Method 4 would most likely be the preferred method if a sufficiently good wind analysis method was available. No such method, with enough accuracy, is known to the authors.

This study raises several questions. For example should the guideline value be reduced for all dwellings on a specific site were wind sheltering has been found for just a few?

The sheltering effect has also been shown to be dependent on wind direction. For some wind directions the wind speed ratio could be low meaning a good masking effect from wind induced noise. Could the reduced guideline value be valid only for some wind directions? That could mean that sector based regulations could be used on the wind turbines to fulfil more strict requirements on noise for specific wind directions.

As it seems that also the time of day has great importance on the wind speed at the immission point, could the guideline value be divided into different time periods for example day and night?

Is a 2:1 ratio the best way? Although the wind speed ratio is more than 2:1 this doesn't mean that there is no wind induced background noise. For as low wind speeds as 3-4 m/s, at 10 m height, the wind induced background noise could be fairly dominant over the wind turbine noise. For what time period should the ratio 2:1 be fulfilled to enforce a reduced guideline value?

Conclusions

There is no doubt that a reduced masking effect caused by sheltered wind conditions could lead to increased disturbance from wind turbine noise. This is obvious to people who live at such locations which also lead to more complaints on noise from wind farms. A reduced guideline value could be important to reduce these complaints already before the wind farm is built. Although this study shows that it is not easy to verify such sheltered locations. There are also many questions that need answers before deciding on a reduced guideline value.

The ongoing project for the Swedish Energy Agency may perhaps, and until time for the conference, have found some more answers to the questions. Also more measurements will hopefully have been performed.

References

[1] Ljunggren S (1998), Mätning av bullerimmission från vindkraftverk, Elforsk rapport 98:24.

[2] Ljunggren S (1994), Recommended Practices for Wind Turbine Testing and Evaluation: 4. Acoustics. Measurement of Noise Emission from Wind Turbines, International Energy Agency, Third Edition.