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Impact of wind-turbine noise on local residents in mountainous terrain at Lista Windfarm, south Norway

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Summary

A case study of the noise pollution produced by the Lista Windfarm in southern Norway is presented. The influence of terrain on sound propagation and its impact on local residents neighbouring this windfarm developed in mountainous terrain is discussed. Based on a combined analysis of sound measurement using professional equipment, and a noise diary recorded by one of the neighbours, the experience of the noise emitted by the windfarm is discussed as observed at distances ranging from 620 to 1800 m from the wind turbines. Data from a noise diary comprising 578 days in addition to long term noise measurements indicate that the noise environment at the surveyed location is substantially different, and more annoying, than what was previously suggested based on the pre-installation noise modelling.

The wind-turbine emitting the most frequent noise is located 1200 m away from the main receiver/monitoring location. This is contrary to the initial modelling, which suggested that the two closest turbines at 620 and 640 m distance to be the noisiest, and most bothersome, at this location. A number of observations made by the local residents suggest that interference between incoming sound-waves, or resonant effects, may be occurring. This is a phenomenon that will aggravate the noise substantially when the observer is located in areas of constructive interference / resonance.

Our study suggests that conventional modelling of sound from windfarms in mountainous terrains is inaccurate and should be discouraged as a tool for determining safe offset distances to windfarms under such conditions. In such terrains it is safer to set the offset distance between dwellings and windfarms at a fixed distance that will place windfarms far enough away from neighbours so that undesirable noise scenarios will be avoided. It is suggested that the best choice would be to set the distance proportional to the size of the wind-turbines expressed in megawatt.

A complaint signed by 80 neighbours has been submitted to the municipality's health authority and the county pollution authority. This is the first formal complaint of such magnitude in Norway. The regulatory process through which such complaints are being processed is discussed.

1. Introduction

The majority of studies investigating the level of noise produced by windfarms, and the extent to which it disturbs local neighbouring residents, have normally been carried out by consultants and researchers who visit the sites of investigation to set up the equipment, and then again to download the data. The experience of living near a windfarm is, however, always defined by those who are exposed to the environmental consequences of the noise on a daily basis. Noise from windfarms has become a subject of enormous conflict in many parts of the world where windfarms are built close to places of residence. It is unlikely that we will be able to resolve these conflicts without studying and paying more attention to the experiences of those who must live with the noise. This paper presents a case study of noise exposure taking into account the experience of, and the data compiled by, residents who are directly impacted by such pollution.

In Norway the regulatory guideline states that assessment of noise at receiver locations around windfarms shall be characterised using the Lden noise indicator. The decibel level for the Lden indicator entails an "average" annual noise-day which is like receiving the weather forecast for a day in terms of an annual average. This leaves the non-skilled person (and probably also many specialists) in a difficult situation with regard to understanding what this will mean in actuality for those who have to endure the noise for the concession period of 25 years, or more. There is a need to carry out more studies based on data collected by people with the first-hand experience of living close to these industrial installations.

An account of the noise as experienced by the neighbours at the Lista Windfarm owned and operated by Fred Olsen Renewables, is presented utilizing several noise datasets collected over a period of 578 days by one of the neighbours. They include a noise diary, indicating which turbine is noisy through time, and professionally recorded sound data. Where appropriate the neighbour's personal experience of noise and associated phenomena in the context of the data recorded or collected is discussed.

In April 2014, 80 neighbours (figure 7.) signed a complaint about the noise from the Lista Windfarm which was submitted to the County Governor of Vest-Agder and the Municipality of Farsund. The 47 page complaint includes 16 letters from individual neighbours describing their own experience of the noise from the windfarm. With the exception of a few vacation homes all of these neighbours live more than 400 m away from the wind turbines. The following selected comments have been lifted from the 16 letters to illustrate the neighbour's experience of the noise from the turbines:

- When the wind turbines were set in motion we were very disappointed to find that the sound was much louder and more troublesome than we had been led to believe
- The noise is like a jet-plane that is not allowed to land. It sounds like the pilot is playing with the gas pedal in pace with the blades of the wind turbine
- It sounds like a truck with the engine running is sitting outside of our house
- It is necessary to keep the window open during the night, but then we cannot sleep for the noise (no air-conditioning in Norway)
- Even with the windows closed we cannot sleep for the noise from the windfarm
- Problems with sleep due to the noise is giving us health problems
- I used to enjoy working in the garden, but it is no longer any fun when the noise is on

This is just a small selection of comments from the 16 letters. One of the most common comments is that people were surprised and shocked by the level of noise produced by the wind turbines. For a discussion on the nature of noise produced by wind turbines see Møller & Pedersen, (2011).

2. Experimental design and area description

2.1 Study objective

The objective of this study was to document and characterize the noise environment at the Lista Windfarm to gain a scientific understanding as to why so many complaints on the noise exposure had arisen. Also, to gain a better understanding of how well the pre-permit modelling of noise at this windfarm would conform to the actual experience of noise exposure by residents who live in the area close to the windfarm.
The following questions have been investigated:

1. What are the characteristics and metrics of the noise environment at the Lista windfarm?
2. How do the windfarm neighbours experience the noise environment from the windfarm?
3. Do the residents experience of the noise correspond to their expectations based on the various noise models and information presented by the windfarm operator and what they were told beforehand?
4. Is it possible to reliably model and predict noise propagation from windfarms in mountainous terrains such as in Norway?

2.2 The Lista Windfarm

The Lista Windfarm (figure 1) was granted its permit in May 2009 and the windfarm became operational in August 2012. It was permitted with a Lden 50 dB(A) noise limit to be adjusted down to 45 dB(A) where wind shadow was present over a certain percentage of the time. The windfarm is situated in mountainous terrain at the Lista Peninsula on the south tip of Norway. 31 industrial wind turbines (Siemens SWT 2.3-93-VS) at 2.3 MW and hub height 80 m have been placed on top of mountain peaks 100 – 300 m above dwellings. Nearly all the dwellings are located in the valleys as shown in the topography profile. Direct raypaths through air from source to receivers at dwellings are common throughout the windfarm as shown by the topography profile (figure 2). Hard, reflective rocky ground dominates the higher areas of the windfarm, especially to the west. The valleys are dominated by acoustically soft, cultivated farm and pasture lands. The slope-areas (between the valleys and the highs) are dominated by forest or shrub lands with a variable and often very thin cover of soil which result in highly variable reflectivity in this area.

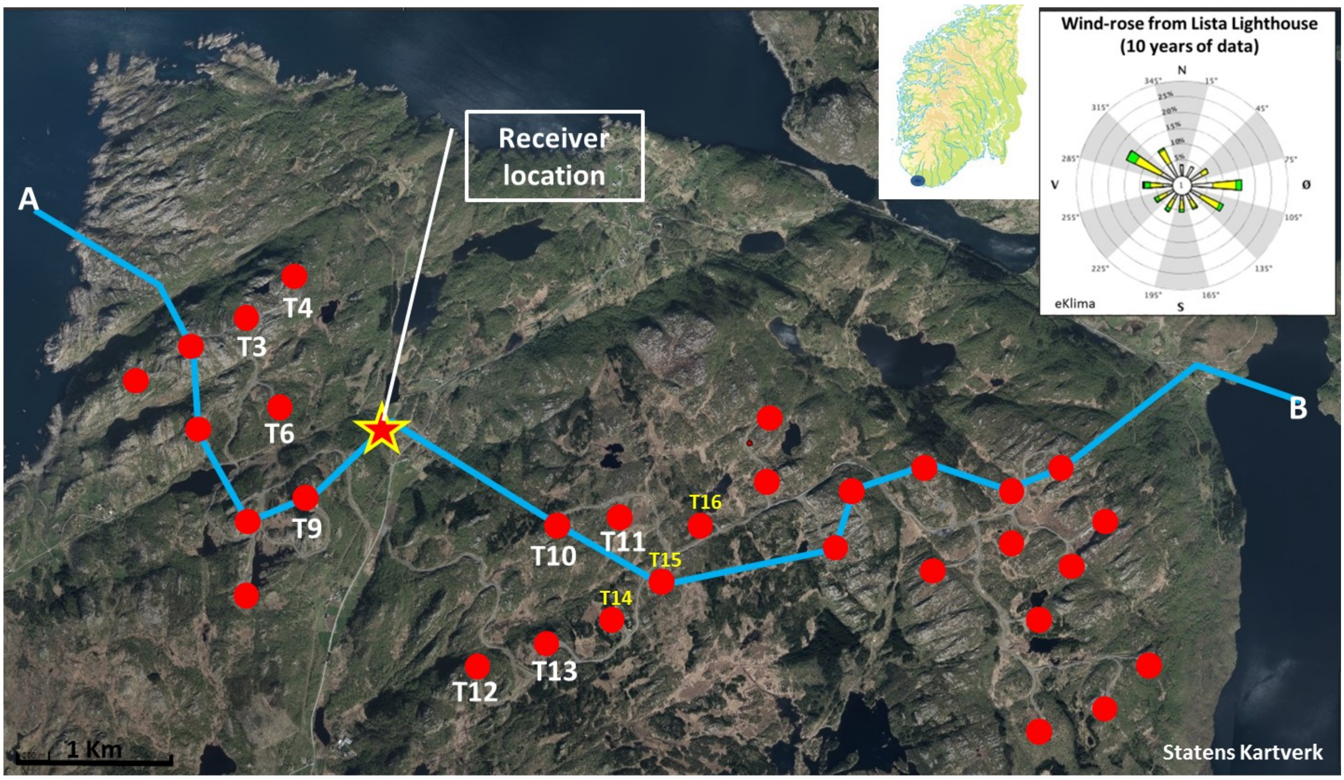

Figure 1. Map of the Lista Windfarm showing the topography and the location of the 31 wind turbines as red dots. The blue line shows the trace of the topography profile in figure 2. The wind rose is based on data from the Lista Lighthouse 8 km away from the receiver location. Red dots with white text correspond to the turbines monitored in the noise diary.

The air-photo shown in figure 1 shows how the topography of the Lista Windfarm is dominated by a series of narrow NE-SW trending valleys. A few dwellings are located in these valleys, but most of the people within the area of noise influence live in the central N-S trending valley (Elledalen) where the receiver location is, and to the north of the windfarm. The wind-rose in the upper right corner of figure 1 shows the two dominant wind directions from East and from NW. The direction of the valleys creates nice areas to live where dwellings are protected most of the time from the near constant wind. This is, however, an unfortunate situation in regard to noise-exposure from wind turbines because the valleys then lie in wind shadow most of the time. Meanwhile the wind, which the area is well known for, most of the time will blow briskly at the turbines up on the hills.

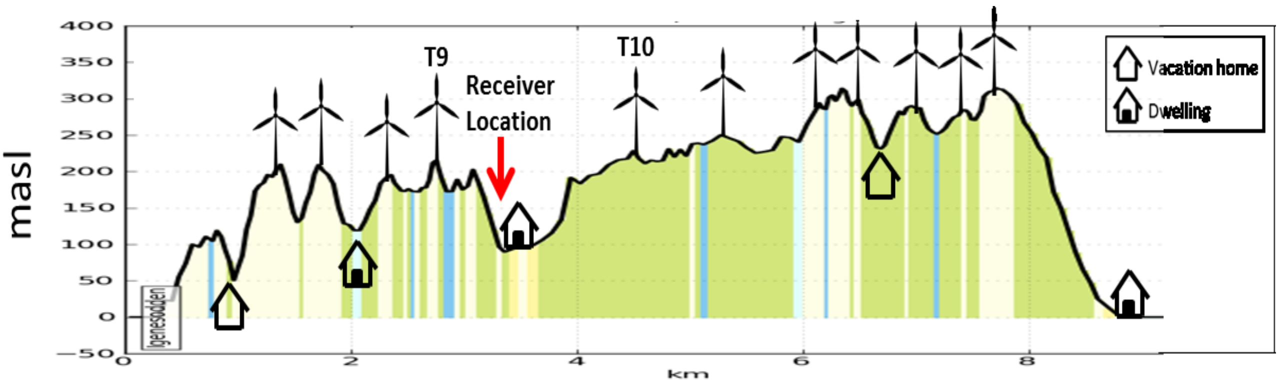

Figure 2. Profile through the Lista Windfarm showing variation of topography and location of the dwellings in the valleys. The height of the wind turbines is to scale. (Where house symbols are shown beneath the profile line the dwellings are offset from the profile)

The profile shown in figure 2 show how the receiver location in the valley is situated in a position with direct view to wind turbine T10 which at the receiver location is the noisiest turbine of them all. All the eight wind turbines annotated with white text in figure 1, with the exception of T9, are wholly or partly visible from the receiver location.

2.3 Previous noise modelling by the windfarm operator

Noise modelling has been carried out several times by the windfarm operator. The first modelling was carried out as part of the documentation for the planning process that led to the grant of the permit to build the windfarm. In February 2013, after the windfarm had been built, a revised noise map was presented by the contractor to correct a mistake made in the pre-permit modelling. The mistake was caused by mixing up the linear sound power level with the A-weighted sound power level (LwA) for the turbines. It resulted in an underestimate of the noise level of 2 – 5 dB in a zone of approximately one kilometre surrounding the windfarm.

Figure 3 shows the updated map following correction of the error. One dwelling (52 dB) falls within the Lden 50 dB(A) contour limit. A number of dwellings (15 – 20) will be exposed to more than Lden 45 dB(A) noise which now is the noise limit for windfarms in Norway. The receiver location in this study is, however, well outside the 45 dB contour and should, according to this map, consequently be experiencing limited and "tolerable" noise from the windfarm.

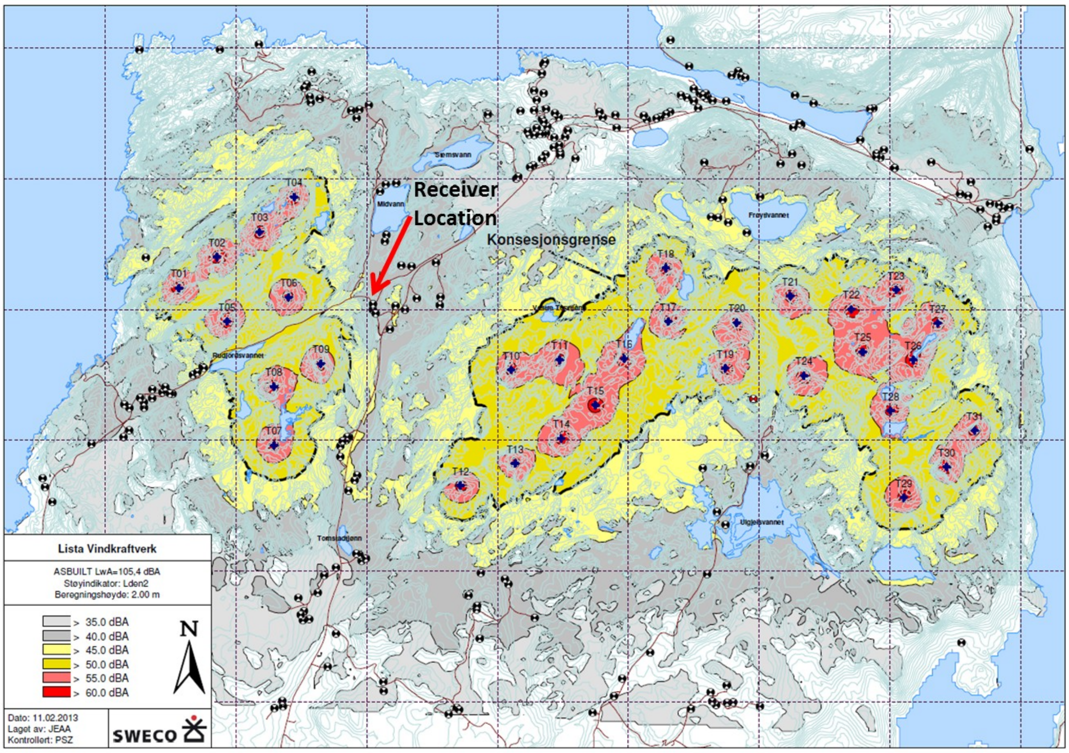

Figure 3. Updated map of Lista Windfarm dated February 2013. Noise indicator is Lden. The bluish contours on top of the map are the topography.

2.4 The receiver location

The home of Willi Larsen, who is co-author of this paper and neighbour to the windfarm, is located in the middle of the N – S trending valley of Elledalen (see figures 2 and 3). The location should be a good place to record sound as it is, typically for most Norwegian valley dwellings, in a relatively sheltered position from the wind blowing from both of the two dominant wind directions (figure 1). This location is referred to as the "receiver location" in this paper. The distance to the nearest wind turbine is 620 meters, but as seen from figure 3 there are a number of dwellings closer to the windfarm having offsets between 400 and 600 meters from the turbines.

2.5 Recording of noise diary

A noise diary was recorded at the receiver location. Over a period of 578 days it was noted if audible noise was heard from each of the eight wind turbines, T3, T4, T6, T9, T10, T11, T12 and T13 (see figure 1. for locations). The turbines are located between 620 and 1800 m away from the receiver location and all, except T9, are wholly or partly visible from the receiver location. T6 is, however hidden behind the canopy of a small cluster of threes during the summer months.

In the absence of highly sophisticated directional sound measurement equipment, the human ear in combination with visual observation of the wind turbine movement is the best tool available to identify from where the sound is coming. This is how the noise was identified from each turbine. The observations were made in the garden outside the house. The noise was checked three times a day (at midnight, at six in the morning and at 4 pm). An entry was made in the database if continuous audible noise was registered at least once in the time periods characterized (24 or 6 hours) – i.e. for the 24 hour period if registered once in that period and likewise for the six hour periods. The rate of registered noise from each of the eight turbines along with their respective distance to the receiver location is shown in a bar-chart in figure 4.

2.6 Wind velocity data

Wind data were downloaded from the weather station at the Lista Lighthouse 8 kilometres away from the receiver location. This is close enough to be reasonably representative of the wind at the windfarm although due to its lower altitude it may underestimate the wind strength somewhat. The wind data at the receiver location was collected using an anemometer set up in an open spot 10 m outside the house.

2.7 Sound measurements

LAeq sound measurements were made at the same location as used by the windfarm operator for previous sound recordings outside this receiver location. A calibrated Norsonic class 1 precision sound level meter (NOR131) with the all-weather microphone protection were utilized for all recordings. The sample rate was one minute.

The discussion will be based on sound data on two datasets:

1. During three months in 2013 LAeq measurements were selectively taken on days when the noise was strongest (most audible) and weather conditions were most favourable for making measurements. Significant time gaps with no record will thus exist in these data.
2. During the period of 20 December 2014 to 24 January 2015 LAeq measurements were undertaken every day whenever weather conditions permitted recording. The sound measurements were split into six hour intervals (LAeq,6).

All noise measurements have been edited for noise peaks assumed to be caused by human activity or other loud sounds not related to the wind turbines. It is not possible to distinguish between noise peaks from wind turbines and noise peaks from other sources. It is thus likely that some peaks such as noise bursts believed to come from turbulence hitting the turbine blades and mechanical noises from the turbines may have been inadvertently edited out of the datasets.

2.8 Presentation of the noise measurements

The method of calculating noise based on the Lden indicator is not very useful for this study as it will give an adjusted estimate of an average annual noise day – or any other interval chosen. The LAeq indicator is more descriptive for this purpose and, until detailed micro-analysis of the sound character can be performed, the best way to characterize the sound environment. All the data have therefore been presented using the LA_{eq} noise indicator for the relevant recording periods.

3. Results

3.1 Neighbours experience of the noise

The winds are very persistent at Lista and out of the 578 recorded days of the noise diary only four days registered with no noise from the wind turbines.

The neighbours shock at first hearing the noise from the wind turbines was shared by the dwellers at the receiver location. In addition to the experiences lifted from the complaint (see the introduction) they describe their own experience of the noise at their home as follows:

1. As soon as we open the door in the morning the sound from the wind turbines increases and becomes even more annoying than inside the house
2. We use hearing protection with built in radio to reduce the impact of the noise. Earplugs have no effect since the low frequencies penetrate them.
3. During the nights when the noise is at its worst we walk around the house trying to find a quiet spot to sleep. The best place when the noise comes from the east is, for example, to put a mattress in the hallway where three walls are between me and the noise. A specially purchased sound-eliminating membrane is hung on the wall. With some luck this may allow a few hours of sleep.
4. Leaving the radio on during the night may help to mask the noise so I can get some sleep.
5. Significant changes in sound intensity may occur when moving from one position to another, both inside and outside the house.
6. The frequent cyclic nature of the sound (amplitude modulation) is very bothersome
7. Going from my work in a noisy industry environment and back home to a noisy environment is stressful as there is virtually no escape from noise
8. Walking the dog on days with noise, which applies to most days, is no longer a refreshing experience like it used to be before the windfarm
9. When strong gusts of wind blows in a loud rattling noise which may last 10 – 20 seconds often appear as the turbines struggle to adjust rotor speed to the change in wind.

Such circumstances must be characterized as intolerable. Experiences like these are common among the neighbours at Lista (see the 16 letters in the complaint document)

Two interesting observations can be made from figure 4 showing the frequency of observed noise from the eight wind turbines that can be singled out as individual sources of noise form the receiver location:

- The most frequently noisy wind turbine is T10 which is 1180 offset from the receiver location.
- There is virtually no difference in observed noise frequency from the four wind turbines to the W and NW of the receiver location.

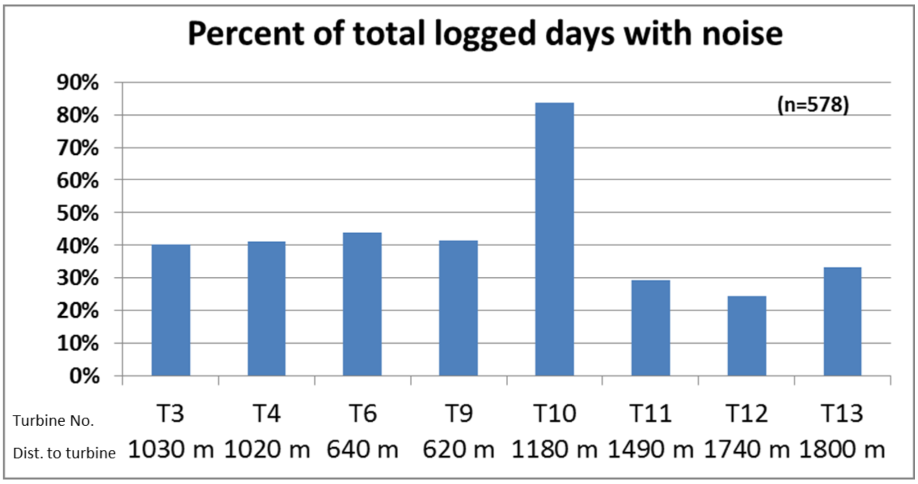

Figure 4. Bar-chart showing the frequency of noted audible noise from each of the eight wind turbines logged in the noise diary. The frequency is shown as a percentage of the total recording days (578). Note the distance to the wind turbine relative to the receiver location at the bottom of the chart.

The four closest wind turbines (T3, T4, T6, T9) located to the West and North West of the receiver location are all relatively easy to distinguish as noise sources. Despite the variable range of distance (620 – 1030 m) they show no significant difference in how frequently they emit noise audible at the receiver location. All four emit noise that is audible above the background noise about 40 % of the time regardless of the distance to receiver. The similarity in noise emission is interpreted to mean that the dominant factor controlling the noise is the wind direction - i.e. when winds are coming in from westerly directions. In this situation the sound from all four wind turbines (T3, T4, T6 and T9) upwind is refracted down into the quiet valley where dwellings are sitting in wind-shadow. Thus the noise can become very dominating in the quiet sheltered valley during westerly winds (Larsson & Öhlund, 2014 (a)).

Wind turbine (T6) at 640 m only registered with noise 44 % of the 578 days while T10 at 1180 m registered with noise twice as frequently (84 %). The observation that a turbine nearly twice as far away as the other is twice as frequently noisy may be influenced by the following factors:

1. The receiver is located at a sheltered, low location relative to all the surrounding wind turbines, but it may be that this setting is more favourable for noise from T10.
2. The T10 turbine is located due SE of the receiver location. From the wind-rose (figure 1) it can be seen that one of the two dominant wind directions is from E - SE. This places the receiver location in the wind-shadow at a location almost directly downwind of the wind turbine. It is well known that this situation enhances the audibility of long travelled low frequent sound in the atmosphere.
3. The T6 turbine is not as visible as T10 and during summer-months most of it is hidden behind a small cluster of threes between the wind turbine and the receiver location. This may lessen the noise. A limited amount of foliage should, however, have little effect on attenuation of sound, particularly for frequencies below 200 Hz (Wondollek, 2009).

Due to the T10 wind turbine being well visible it is easy to link the cyclic noise to visible observation of this turbine. It is also the experience of the neighbour living at the receiver location that T10 is the loudest wind turbine relative to this location.

A number of dwellers have noted that the noise level at times may vary substantially over short distances of a few meters. Moving only three meters may bring detectable changes in the noise level. Moving 10 – 20 meter may take the noise from strong and annoyingly audible to just barely being heard. This effect may be explained two possible ways:

- The neighbours may be experiencing interference of sound waves, or possibly resonant sound. This happens when two sound waves are interfering constructively or destructively with each other creating points where the sound is amplified, or reduced. Phenomena associated with reflections of sound may also occur.
- It may also be due to unexpected shielding effects, but this is difficult to explain due to the open position in three directions of the house at the receiver location.

Interference may be caused by many different wave interactions such as:

1. Between the refracted and the direct (or ground reflected) sound wave from an individual turbine
2. Between sound from different turbines at different offset directions spinning in phase
3. Between refracted and diffracted waves
4. Between reflected waves bouncing off cliffs and direct waves

Without detailed 3D ray-trace modelling it will be difficult to distinguish which of these situations may be the most likely to occur.

Interference (or tuning) of sound is a common phenomenon in solid earth seismic imaging. There is every reason to expect that it will also be common for sound transmission in the air along hard, rocky ground with sharp changes in relief such as in mountainous terrains, or reflections between houses and even inside houses. In air it will, however, be harder to prove than in solid earth due to the atmosphere being a dynamic medium in constant change. 3D ray-trace modelling utilizing detailed models of the terrain and buildings may be our best solution towards demonstrating how this may work.

3.2 Background noise

Based on sound measurements carried out on quiet nights with little wind and turbines at a standstill the background noise is found to be between Leq 28 and 32 dB(A).

3.3 Results of sound-data analysis

<u>Sound dataset 1</u>

Figure 5 shows a bar chart of LAeq sound measurements recorded over a period of 3 months. Most of the measured periods are approximately 16 hours of data from 06.00 – 22.00. They thus do not include the nights and may therefore underestimate the noise somewhat as one would expect the noise to normally be more dominant during nights when the atmosphere stabilizes. The blank spaces are days when the recording conditions were not optimal due to either sound level or the rare days when the turbines were at standstill due to low wind.

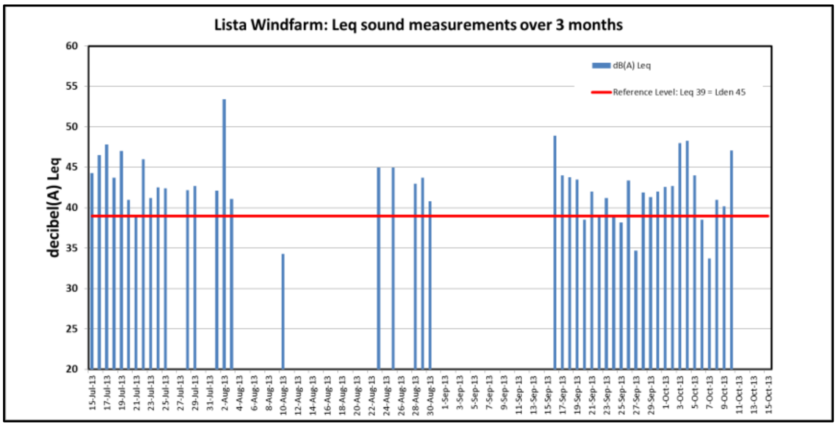

Figure 5. Bar chart of LAeq data recordings over 3 months from 15 July to 15 October 2013. Sound recording was only performed on days when conditions were good and noise easily audible. The red line at 39 decibel has been included as a reference basis. It indicates the equivalent level in terms of LAeq relative to the Norwegian noise limit of LAden 45 (LAeq = LAden,24 minus 6 decibel).

These measurements were made on days when the sound appeared clearly audible on top of the background noise for longer periods. They should thus represent sixteen hour averages of noise levels caused by the wind turbines. The chart show periods longer than one week where the noise was fairly strong at 39 – 47 decibel LAeq with peaks up to 53 decibel. Since there are substantial periods with missing data there may, however, be more days with noise above Leq 39 dB(A). These periods of prolonged noise are, in the dwellers experience, the most troublesome due to their prolonged impact on sleep. They make for one of the most important factors driving the dwellers complaints on the noise.

Sound dataset 2

During the winter months Lista is heavily prone to strong wind and weather conditions. The atmosphere, which is a highly dynamic medium with regard to sound propagation, is heavily influenced by unstable weather conditions at this time of year. Strong winds mean turbulent air conditions. Such conditions do not allow a stabilized atmosphere that is conducive to sound propagation to form either day or night. These conditions tend to disperse the sound and thus inhibit sound propagation in the atmosphere at this time of year. The result is, on average, a more benign noise-environment with respect to sound from wind turbines. However, the winter is also part of the life of a windfarm neighbour and its noise footprint should be investigated along with the rest of the year.

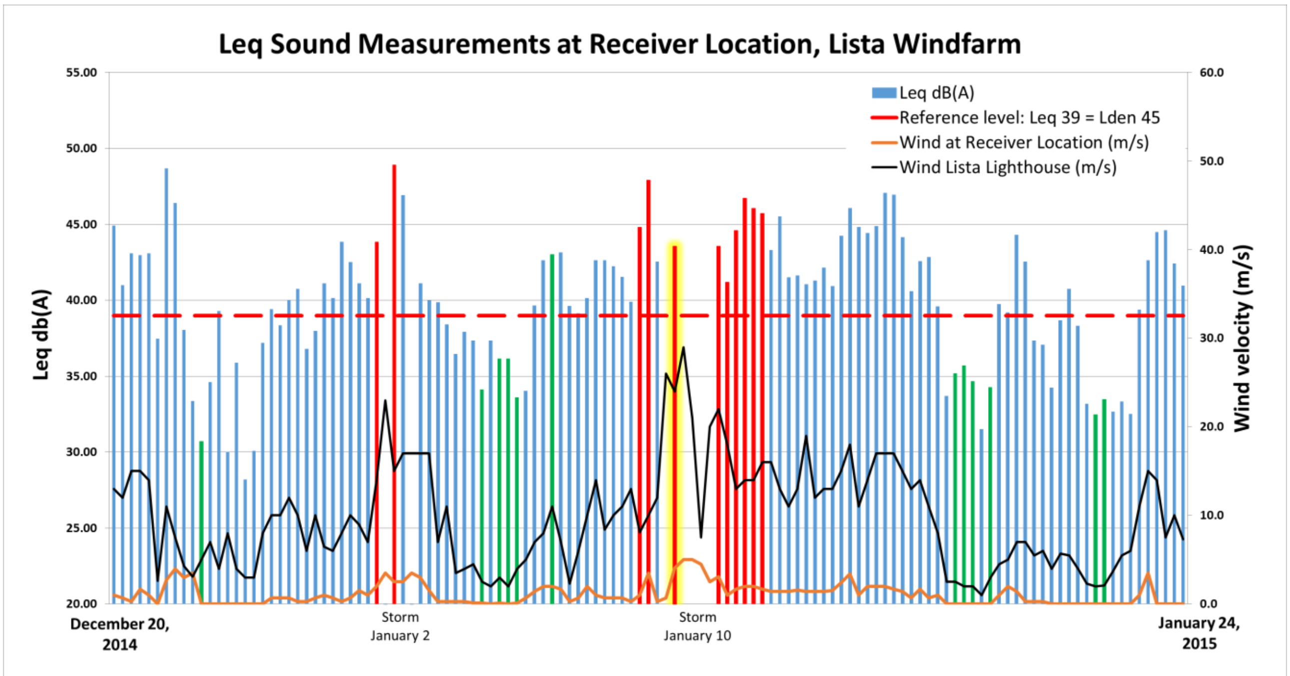

Figure 6. Bar-chart showing LAeq sound data recorded over a period of five weeks from December 20, 2014 to January 24, 2015. The data are 24 hour recordings split up and displayed as six hour intervals per bar. Black curve: Wind velocity at the Lista Lighthouse (8 km away). Orange curve: Wind velocity at the receiver location

Key to figure 6 bar-colours for sound measurements:

Blue bars: Time periods when audible sound was heard from the wind turbines
Red bars: Time periods when the wind turbines were shut down, or strong wind and other weather conditions masked out noise from the turbines most of the time.
Green bars: Time periods when noise from wind turbines was inaudible or very weak
Red & Yellow bar: Sound measurement when shut down turbines were making a whistling (or screeching) sound

Figure 6 shows how the noise level varies at the receiver location over five weeks during the winter. The blank spaces represent periods when weather conditions did not allow for meaningful recording of sound at the receiver location. The black curve representing the wind-velocity at the Lista Lighthouse identifies the timespans corresponding to periods of very strong wind and gales. There is a marked difference in wind strength between the black curve and the orange curve showing the wind velocity at the receiver location. Even during strong gales the wind-velocity at the receiver location does not exceed 6 m/s. This indicates a substantial wind-shadow effect occurring at this sheltered location.

The single red and yellow bar in the middle of the diagram represents a measurement made while the wind turbines were shut down due to gale force winds. During most of the shut-down period the wind turbines moved very slowly and emitted a whistling sound unlike anything heard when in motion. Several neighbours have commented that this was a very uncomfortable sound which some felt at times were at least as tormenting as the normal aerodynamic sound. The noise is likely caused by friction from the hydraulic disc brakes as the turbine blades turn slowly to avoid gear-damage in the strong wind. The whistling sound was drifting in and out between the strong wind gusts and it is uncertain how much of the recorded sound pressure derives from this sound, and how much is due to regular wind-noise.

The difference between noisy and relatively quiet conditions can vary up to 20 decibel, but normally it is around 14-15 decibel (figure 5 & 6). There are periods of nearly a week where the noise level significantly exceeds the reference level of 39 decibel. Based on the experience of the neighbours these are the most difficult periods. Research has shown that even at 39 dB(A) a third of the people experiencing this level of noise will be annoyed (Pedersen & Waye, 2008).

Since recording sound in the highly variable winter weather is challenging in terms of obtaining records representing the actual turbine noise it may be that some of the blue data points are driven by background noise from the wind, rather than by actual turbine noise. Data acquired in the summer half of the year calibrated against operator observations will give a better perspective on what is real noise and what is not as the atmospheric conditions are more stable. One should therefore be careful with drawing firm conclusions on the absolute strength of wind turbine noise from the records displayed in figure 6.

All of the sound measurement data shown in this paper are Leq for periods from under six hours to 16 hours. They are thus averages for substantial periods. During these periods there will be shorter periods when the noise is louder and times when it is fainter. There will also be times when shorter burst of sound occur. This may happen when the turbines are hit by gusts of very turbulent air, or when wind conditions in the highly dynamic atmosphere for a few seconds refracts substantially more sound energy down towards the ground in some places. With regard to sleep these moments will significantly increase the wakeup frequency for those sleeping under such conditions (WHO 2007). Research in Sweden also has shown that noise from wind turbines is substantially more annoying than other man-made environmental noise (Pedersen & Waye, 2007)

4.0 Norwegian law process governing complaints on noise

Following are some comments on the regulatory process for making complaints on noise in Norway and how the authorities ruled on the concerns of the neighbours as stated in the complaint. In Norway two different laws regulate health-risk from noise: “The Pollution Law”, and the “Public Health Law” with its accompanying guideline “Regulation on environmental health protection”.

The County Governor is the public authority to which a complaint under the Pollution Law should be addressed. The County Governor will consider a complaint in terms of whether a windfarm exceeds the permitted noise threshold which currently in Norway is Lden 45 dB(A). Lista Windfarm was, however, granted concession with Lden 50 dB(A) as the limit. These are unfortunately not firm limits and can, through government permit, be exceeded. The County Governor turned down the neighbour's complaint stating that the noise exposure did not exceed the noise limits as permitted.

The Municipality is the public authority to which complaints under the Public Health Law should be addressed. Paragraph 7 under the guideline "Regulation on environmental health protection" states: *"Enterprises and properties shall be planned, built, adapted, managed and decommissioned in a health-related satisfactory way, so that they will not lead to risk of injury to health or health-related inconvenience. By health-related it is meant circumstances which according to medical assessment could impact health in a negative way that is not insignificant"*. This law is intended to act as a safety net for cases where other environmental legislation is out-dated, insufficient or where there is doubt about its sufficiency. Under this law it is sufficient to prove that the exposure is a health risk that is not insignificant, at which point the municipality is obliged to take action. In the case of the Lista Windfarm the municipality has ruled that a survey of the health-consequences upon the neighbours should be undertaken. A complaint to this ruling made by the developer was subsequently turned down in January 2015 by the County Governor. The health check is now ordered to be carried out by the end of 2015 for all residents living within 2000 m of a wind turbine. This area includes 44 permanent households with a total of 118 inhabitants. People owning vacation homes in the area shall also be included.

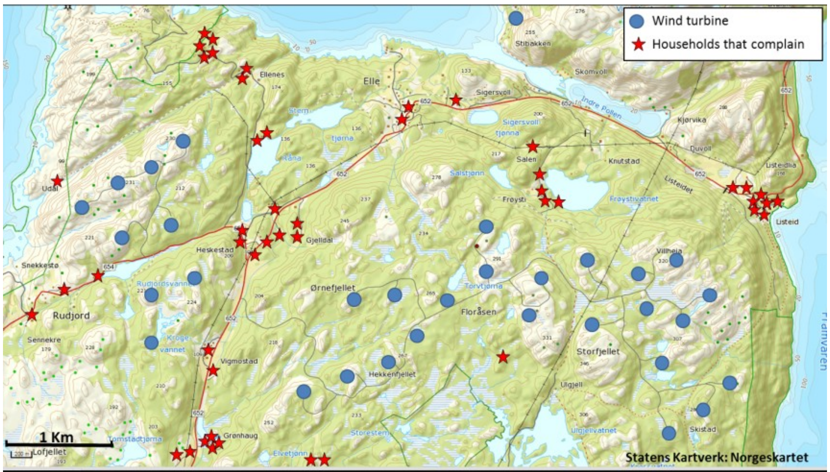

Figure 7. Map showing locations where the 80 dwellers that submitted complaints live around the windfarm.

5.0 Conclusions

The study has shown how variable and unpredictable the noise environment may be at this windfarm built in mountains where the dwellers live in valleys protected from the wind. Noise levels may vary up to 20 decibel from quiet to noisy days. Periods of continued high noise of over a week have been documented. Several poorly understood phenomena such as possible interference of sound waves, and dominant long travelled noise (T10 at 1200 m) have been identified and described. The lower wind velocity at the receiver location relative to the Lista Lighthouse indicates a very strong wind shadow effect in the valley. The wind shadow will aggravate noise conditions wherever present within the valleys around the Lista Windfarm.

The following observations suggest that the conventional Lden noise modelling of sound from this windfarm yielded very inaccurate results:

- The many neighbours were shocked at experiencing noise much worse than they were led to believe from the developer's description of the predicted noise conditions. One must assume that the developer's description of expected noise was based on the noise modelling.
- The study describes intolerable noise conditions at an immission point with a modelled noise exposure of approximately Lden 43 dB(A), a value which by Norwegian noise guidelines is assumed to be a tolerable noise level.
- We have found no indication that the noise modelling properly takes into account the effect of the wind-shadow in the valley.
- The T10 wind turbine which is almost twice as far away as the closest wind turbine was shown to be the most frequent sound source.
- Hard, rocky ground and steep cliffs very likely create reflection effects that, with the tools available, are very difficult to measure or predict how and where they will occur.
- There is evidence from the receiver location, as well as other locations on the windfarm, that tuning effects are common in these terrains. These effects are hard to predict.
- In general one would, based on basic ray-path theory, expect to find very complex ray-paths with associated sound effects in such mountain terrains. These will, with the tools currently being used, be almost impossible to predict and assess the impact of in terms of noise during the planning process.

The results of this study support the neighbour's claim that the actual noise environment is significantly worse than stated by the developer and the Norwegian Water Resources & Energy Directorate during the permit process. This is evidenced by the dwellers own experience, by the long periods of high measured noise exposure and by the noise log which identifies only four days without noise during the logged period of 578 days. As we do not yet have a full year of detailed daily measurements and analysis, it may be premature to finally conclude that the actual noise environment from a purely numerical point of view exceeds what is shown in the operators modelling. However, as shown above most of the data reviewed so far indicates that this may be the case.

Most of the windfarms built and in planning process in Norway are set in mountain terrains that differ significantly from the simple flat, or more gently profiled, land areas of windfarm developments in continental Europe and most other places in the world. The tools currently used for modelling of noise at windfarms give the best results in these gentle terrains. The results of this study may suggest that the modelling tool used at Lista deals ineffectively with ray-tracing in complex mountain terrains. Alternatively, the software is not being used correctly for Norwegian mountainous terrains.

The observations and conclusions of the study suggest that conventional noise modelling should be discouraged as a tool for determining safe offset distances to windfarms in mountain terrains. In such terrains it may be safer to set the offset distance for dwellings relative to wind turbines as a fixed distance - possibly proportional to the megawatt-size of the wind-turbines. Megawatt is likely the best indicator of magnitude of source noise since it will be relatively proportional to the size of the blades which create the aerodynamic noise (Møller & Pedersen, 2011).

6.0 Suggested further work

There are several conditions or questions that should be studied with further work:

1. It would be useful to collect more detailed data to get full year of "resident calibrated" datasets of the noise and wind conditions at Lista windfarm. Such a dataset may form the basis for a study of the seasonal variations in noise, which would be an important part of building a more complete description of the noise environment at the Lista Windfarm.

2. Differences in noise environment during day and night should be studied with more data.
3. The sound environment in the low frequent spectrum recorded with the acoustic filter of the noise indicator LCeq should be studied.
4. Detailed three dimensional modelling to study sound propagation, refraction and the interference effects in the complex mountain terrain should be undertaken
5. Amplitude modulation should be further investigated, possibly using the methodology of Larsson and Öhlund (2014).

References

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