Health effects related to wind turbine sound

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Summary

This report reviews recent literature on health effects related to wind turbines. This has been done at the request of the Swiss Federal Office for the Environment. The request was to give an overview of the conclusions from the more recent scientific reviews with respect to the health effects of sound from wind turbines. Questions about health effects often play a prominent role in local discussions on plans for (an extension of) a wind turbine farm.

Noise annoyance is the most often described effect of living in the vicinity of wind turbines. Annoyance from other aspects, such as shadow flicker, the visual (in)appropriateness in the landscape and blinking lights, can add to the noise annoyance. Some people report annoyance (irritation, anger and anxiety) if they feel that the quality of their surroundings and living conditions will deteriorate or has deteriorated due to the siting of wind turbines. Long lasting annoyance can lead to health complaints. There are less data available to evaluate the effects of wind turbines on sleep. Sleep disturbance is found to be related to annoyance, but there is no clear relation with the level of wind turbine sound. From knowledge about transportation sound, sleep disturbance can be expected at high levels of wind turbine sound. There is no evidence for other direct health effects. Other (indirect) health effects that have been reported on an individual basis could be a result of chronic annoyance.

These are the main conclusions of a literature survey performed by the Municipal Health Service (GGD) Amsterdam and the Dutch National Institute for Public Health and the Environment (RIVM), both in the Netherlands. Residential sound levels from wind turbines are lower than those from comparable sources, such as traffic or industry, but are experienced as more annoying. This is possibly caused by the typical swishing or rhythmic character of the sound. Perhaps the low frequency component of wind turbine sound also leads to extra annoyance, as is the case with other sources. However, there is no evidence of an effect specifically related to the low frequency component. It has been suggested that a direct effect of infrasound on persons has been underestimated, but available knowledge does not support this. Perhaps the effect of rhythmic pressure pulses on a building can lead to added indoor annoyance and should be further investigated. Besides the wind turbine sound as such, personal characteristics, the local situation and the conditions for planning a wind farm also play a role in reported annoyance. For example, at equal noise levels, people report more annoyance when they can actually see a wind turbine; or less annoyance, when they benefit from the wind turbine or farm. Other factors that should be taken into account when interpreting annoyance scores are noise sensitivity, privacy issues and social acceptance.

1. INTRODUCTION

This text gives an overview of knowledge about wind turbine sound and its effects on neighbouring residents. It emphasizes knowledge from scientific publications, where peer-reviewed articles are most eminent. However, some scientific reports and papers presented at conferences also provide important and often reliable information.

This overview is commissioned by the Noise and NIR Division of the Swiss Federal Office for the Environment (Bundesamt für Umwelt). The request was to give an overview of the conclusions from the more recent scientific reviews with respect to the health effects of sound from wind turbines with special attention to infrasound and low frequency sound. We have collected all relevant reviews since 2009, but these did not include the most recent studies, especially from Canada and Japan. For the period between 2009 – 2015 only reviews were considered. For the period between 2015 and 2017 the reviews as well as the original studies were included. Where relevant we refer to earlier original papers (before 2015).

We start in Chapter 2 with an explanation of the sound produced by and heard from a wind turbine and what sound levels occur in practice. We use the term 'sound' because we do not want to imply a priori the negative meaning that noise ('unwanted sound') has. Other aspects of wind turbines can cause annoyance by themselves or can have an influence on the appreciation of the sound; these other impacts are considered in Chapter 3. Chapter 4 is about how sound from a wind turbine can affect people and especially neighbouring residents and in what way and to what degree other factors are important to take into account. This is repeated in Chapter 5 for sound at (very) low frequencies that allegedly can affect people in others ways that 'normal' sound does.

In Chapters 3 through 5 we have taken information from others without evaluating the different research results. Our evaluation is in Chapter 6 where our conclusions from reading and interpreting all the scientific information are summarised. This chapter concludes the main text.

In Annex A it is described how we retrieved all relevant scientific information and all the articles providing this information are listed in Annex B. A reference to this list is given in the main text by a small superscript number, with more references separated by a comma or –when including a range- a hyphen(e.g. [4, 6] or [7-10]). When we use author names, 'et al' means there are two or more co-authors.

We thank Professor Geoff Leventhall and Professor Kerstin Persson Waye for their useful comments to an earlier version of this text.

2. THE SOUND of WIND TURBINES

2.1 Sound production

An overview of wind turbine sound sources is given in a number of publications such as Wagner[1], Van den Berg[2], Leventhall and Bowdler[3] or Hansen et al[4].

For the tall, modern turbines most sound comes from flowing air in contact with the wind turbine blades: aerodynamical sound. The most important contributions are related to the atmospheric turbulence hitting the blades (inflow turbulence sound) and air flowing at the blade surface (trailing edge sound).

- Turbulence at the rear or trailing edge of a blade is generated because the air flow at the blade surface develops into a turbulent layer. The frequency with the highest (audible) sound energy content is usually in the range of a few hundred Hz (hertz) up to around 1000-2000 Hz. At the blade tips conditions are somewhat different due to air flowing towards the tip, but this tip noise is very similar to trailing edge noise and usually not distinguished as a relevant separate source.
- Inflow turbulence is generated because the blade cuts through turbulent eddies that are present in the inflowing air (wind). This sound has a maximum sound level at around 10 Hz.
- Thickness sound results from the displacement of air by a moving blade and is insignificant for sound production when the air flows smoothly around the blade. However, rapid changes in forces on the blade result in sideways movements of the blade and sound pulses in the infrasound region. This leads to the typical wind turbine sound 'signature' of sound level peaks at frequencies between about 1 to 10 Hz. These peaks cannot be heard, but can be seen in measurements.

2.2 Sound character

Inflow turbulence sound is important in the low and middle frequency range, overlapping with trailing edge sound at medium and higher frequencies. As both are highly speed dependent, sound production is highest where the speed is highest: near the fast rotating tips of the blades.

When the sound penetrates into a dwelling, the building construction will attenuate the higher frequencies better than the lower frequencies. As a result, indoor levels will be lower and the sound inside is of a lower pitch, as higher frequencies are more reduced than low frequencies. This is true for every sound coming from outside.

Wind turbine sound changes over time. An important feature is the variation of the sound at the rhythm of the rotating blades that is described as swishing, whooshing or beating. This variation in synchrony with the blade passing frequency is also called the Amplitude Modulation (AM) of the sound.

An explanation for the typical swish that is audible close to a turbine has been given by Oerlemans[5]. Because of the forward directivity of trailing edge sound (more sound is radiated in the forward direction of the blade) and the Doppler amplification (forward of the moving blade) there is a higher sound level when the blade tip is moving towards an listener and a lower level when it moves away. As a result, one can hear a variation in sound level in the rhythm of the passing blades. This swishing can always be heard close to a turbine. However, this explanation does not hold for an observer distant and downwind from a turbine. In that case, there is no blade moving towards the observer. But even at long distances one can sometimes hear a rhythmic variation that can develop into a distinct beating.[6] In papers and reports this is sometimes referred to as ‘other’ or ‘special’ AM.[7,8] The explanation for this ‘special’ AM is a change in wind speed over the rotor diameter. When a blade encounters different wind speeds in its rotation, this will lead to a variation in sound production at the blade. This will typically occur when there is a high wind shear, i.e. the wind speed increases substantially with height. Certainly at night there can be a firm wind at rotor height even though there may be almost no wind at ground level. It can also occur when part of the rotor is in the ‘wind shadow’ of a ridge or another turbine. A regular variation can explain a rhythmic beating. This is most often heard in evening, night time and early morning and when there is low cloud cover, which implies a stable atmosphere and high wind shear.[6,8,9,10]

AM may be terrain dependent: over hilly or mountainous terrain wind shear may be rather different from the wind shear over flat terrain. Even so, with turbines on a ridge and residents in a valley, a high contrast between wind turbine and background sound may exist,[11] similar to the effect of a stable atmosphere over flat ground.

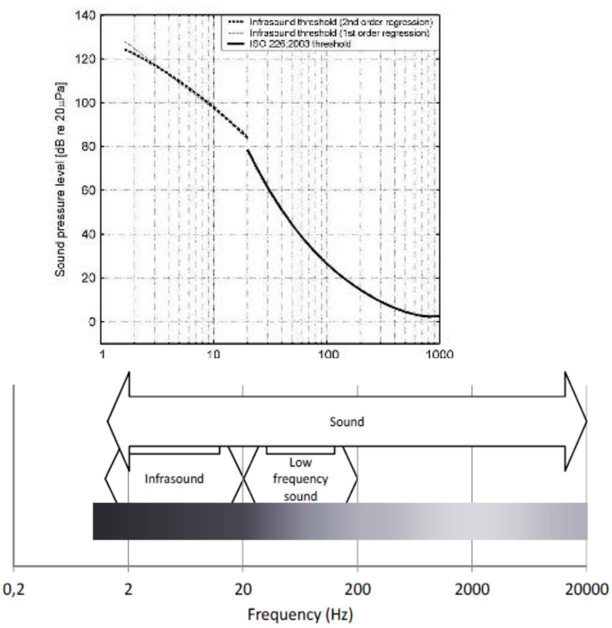
Wind turbine sound can sometimes be tonal, i.e. one can hear a specific pitch. This can be mechanical sound from the gear box and other devices in the turbine and this was a relevant source for early turbines. However, this has been reduced and is generally not an important source for modern turbines. Another possible source is an irregularity on a blade, but this is apparently rare and can be mended. Nevertheless, tonal sounds still can occur.

2.3 Human hearing

Human hearing is relatively insensitive at low frequencies as shown in figure 1: the upper part gives the average hearing threshold; the lower part shows which frequencies are in the infrasound and low frequency sound region (the upper limit of the low frequency region is not formally defined and can vary from 80 to 200 Hz).

It is usual to apply a correction to a measured sound that takes the hearing sensitivity at different frequencies into account. This so-called A-weighting mimics the frequency dependency of human hearing at moderate loudness. Most environmental sounds with a level of 40 dBA (A-weighted deciBels) will approximately have the

Figure 1: above: the average hearing threshold for normal hearing people from 2 – 1000 Hz (figure from Møller and Pedersen[12]); below: infrasound, low frequency sound and total audible sound region (from SHC[13])



same loudness for human hearing. Such a low to moderate loudness is present at actual wind turbine sound levels at many residences near wind farms. Therefore, A-weighting should give a (nearly) correct approximation of the loudness of wind turbine sound at levels of 35 to 45 dBA. With hearing tests this was confirmed in the Japanese wind turbine sound study.[14] A-weighting is less correct at lower sound levels; application of A-weighting to low levels (roughly < 30 dBA) may allow for more low frequency sound. Of course, this concerns sound levels that are already low and usually will comply with limits. If the unit dB (no weighting) is used, as is often done at low frequencies, then no correction is applied to the sound level. If expressed in dBA (or dB(A), to be more correct), the A-weighting has been applied.[*]

It is because of the combination of our hearing capacities at different frequencies and the sound level of the different wind turbine sources that trailing edge sound is the most dominant sound when outside and not too far from a wind turbine. The sound will shift to lower frequencies at larger distances or indoors and then inflow turbulent sound can be more important.

2.4 Sound levels in practice

For a modern turbine, the maximum sound power level is of the order of 100 to 110 dBA. For a listener on the ground at about 100 m from a turbine the sound level will not be more than about 55 dBA. At more distant, residential locations this is less and in most studies there are few people that are exposed to an average wind turbine sound level of more than 45 dBA. For two turbine types in a temperate climate it was shown that the sound level from these two types at full power is 1 to 3 dB above the sound level averaged over a long time.[15]

Measurements on many types of modern wind turbines show that most sound energy is radiated at low and infrasound frequencies and less at higher frequencies (approximately 100 – 2000 Hz). However, because of the lower sensitivity of human hearing at low frequencies, audibility is greater at the higher frequencies. Over time wind turbines have become bigger and onshore wind turbines now can have several megawatts (MW) electric power. 2 MW turbines produce 9 - 10 dB more sound power when compared to 200 kW turbines.[16,17] Over time the amount of low-frequency sound (10 – 160 Hz) increases at nearly the same rate as the total sound level. This also depends on the type of regulation of the rotor speed. For pitch regulated turbines the low frequency part of the sound increases at a somewhat higher rate (about 1 dB more for a tenfold increase in power) when compared to the total sound level and the reverse is true for stall regulated turbines.

[*] However, in the EU a sound level averaged over day, evening and night is expressed in dB Lden, although it is an A-weighted level.

3. SOCIAL AND PHYSICAL ASPECTS other than noise

In this chapter we mention a set of issues which are, next to sound, relevant for residents living in the vicinity of wind turbines. The visual aspect of wind turbines, safety, vibrations and electromagnetic fields may also have an impact on the environment and people in it. Other factors that influence the impact include economic benefit, intrusion in privacy and acceptance of the wind turbines and other sources of disturbance. Personal and contextual aspects can also determine the level of annoyance due to wind turbines.

3.1 Visual aspects

Modern wind turbines are visible from a considerable distance because they rise high above the environment and change the landscape. Due to the movement of their rotor blades, wind turbines are more salient in the landscape than objects which do not move. The rotating blades draw our attention and can cause variations in light intensity when the blades block or reflect sunlight. The visual and auditory aspects have been shown to be highly interrelated[18,19,20] and are therefore hard to unravel with respect to their effects. Annoyance from visual aspects may add to or perhaps even reinforce annoyance from noise (and vice versa).

3.1.1 Integration of wind turbines in the landscape

The visual perception of wind turbines is associated to a number of factors such as the type of area and sound level.[19,20] The perception may depend on the siting procedure and the attitude towards wind energy projects.[21] In other words: the violation of the landscape is very dependent on the context and a univocal judgment cannot be given. Integrating wind turbines in the landscape is a factor of great importance and is related to ideas people have about the landscape.[22] Residents have expectations and requirements regarding their living environment and the visual appreciation may vary between individuals from positive to very negative. An exchange of viewpoints between different parties (residents, authorities, landscape planners, developers, etc.) can clarify these aspects, but do not necessarily lead to solutions. The type of area and its geographical features are important: in a more urban or industrial environment wind turbines will be less intruding than in a more natural landscape in which the turbines contrast more with the environment.[23,24] All of this can influence people's reactions and emotions: when the turbines are perceived as not matching with the environment the reactions can be more negative and vice versa. The Belgian Superior Health Council stated that people become attached to the place where they live and a wind turbine or wind farm in 'their' place may mean an intrusion and deterioration of that place.[13] Also, siting a wind farm in a natural or 'green' area may counteract the positive health effect of such an area. These aspects should be part of the siting procedure as it is too difficult to quantify these effects, even in a specific situation.[13]

3.1.2 Light flicker

Light flicker can occur when the sun is reflected from a blade at a certain position of the blade. When the blades rotate this gives a continuous flicker. This is conspicuous and can be annoying. However, this feature has become rare for modern wind turbines, since it has become standard practice to cover the rotor blades with an anti-reflection layer.
Light intensity near a wind turbine can also change when the blades pass before the sun. This rotating shadow casting or shadow flicker (that only stops when the turbine stops) will be mentioned in Chapter 4 in relation to noise.

3.2 Safety

Wind turbines are under control of quality protocols of the producers and the authorities issue a construction permit based on rules for safety. On a regular (yearly) basis wind turbines are checked for their proper functionality. When a shortcoming is found or when a safety issue cannot be excluded the turbine has to be stopped. A turbine also can be stopped automatically when there is ice on the blades (which could be thrown from a rotating blade). Nevertheless, there is a chance that something will happen during the lifetime of a turbine. From a large number of wind turbine accidents, Asian et al conclude that most serious accidents (deaths) occur during the construction and maintenance of a wind turbine.[25] During operation, when generating electricity, natural influences (wind and lightning) are most important, followed by system or equipment failures.[25] An early study in Switzerland on ice throw from wind turbines showed that this was -at that time- occurring regularly.[26]

3.3 Vibrations due to wind turbines

Vibrations from wind turbines can lead to ground vibrations and these can be measured with sensitive vibration sensors. In several studies vibrations have been measured at large distances, but this was because these vibrations could affect the performance of seismic stations that detect nuclear tests. These vibrations are too weak to be detected or to affect humans, even for people living close to wind turbines.[27]

3.4 Electromagnetic fields

Electric, magnetic and electromagnetic fields exist everywhere. Known and natural forms are UV-radiation, infrared radiation and visible light. Electromagnetic fields (EMF) are also present near electric devices and transport of electricity over longer distances (such as power lines), including underground cables that link a wind turbine to the power grid. The strength of these fields reduces when the distance to the source increases. It is not plausible that the electromagnetic field strength near wind turbines and related underground cables form a health risk, as this is similar to what is present in homes.[19]

3.5 Contextual and personal factors

Research in the past decade has shed some light on the question why some people are more disturbed by wind turbines than other. Next to physical aspects, personal and contextual aspects also influence the level of annoyance. Often these aspects are referred to as non-acoustic factors, complementary to the acoustic factors in decibels. Because the term non-acoustic refers to a broad range of aspects, and as a result are very unspecific, we prefer the term personal and contextual factors.[28] They can be subdivided in the following sub-categories:

- Demographic and socio-economic factors (age, gender, income, level of education);
- Personal factors (fear or worry in relation to source, noise sensitivity, economic benefit from the source);
- Social factors (expectation, attitudes towards producers or government, media coverage);
- Situational factors (frequency of sound events, meteorological circumstances, other sound sources, distance to amenities, attractiveness of the area).

Some of these aspects are relevant in the framework of wind turbines and are discussed in more detail below.

3.5.1 View of wind turbines

Noise and visual annoyance are strongly related as already mentioned above. People who also see turbines from their homes might be more worried about the health effect of continuous exposure and as a consequence also report more annoyance.[13]

3.5.2 Economic aspects

Economic aspects can also affect annoyance from wind turbines. In a study of Pedersen and Van den Berg and colleagues in the Netherlands[29,30] some 14% of the respondents benefited from one or more wind turbines, in particular enterprising farmers who lived in general closer to the turbines and were exposed to higher sound levels than the remaining respondents. In the subgroup of people benefiting from the turbine the percentage of annoyed persons was low to very low, even though they were on average closer to the turbines and hearing the turbines as well as others, using the same terms to describe the typical characteristics of wind turbine sound. In the study this group was described as “healthy farmers”: on average they were younger, more often male and had a higher level of education and reported less problems with health and sleep when compared to those not having economic benefits.[30] However, it might not only be the benefit, but differences in attitude and perception as well as having more control over the placement of the turbines that might play a role.[30] In the Canadian study of health effects from wind turbine sound, personal benefit was also correlated to being less annoyed, when excluding factors that were likely to be a reaction (such as annoyance) to wind turbine operation.[20] In the Japanese study there was also a relation, but this was less strong (i.e. not significant).

3.5.3 Privacy and freedom of choice

Pedersen et al[31] found that people who perceive the wind turbines as intruders and a threat to their privacy (motion, sound, visual) reported more annoyance. When people feel attached to their environment (‘place attachment’), the wind farm can form a threat to that environment and this can create resistance.[32] Also, a feeling of helplessness and procedural injustice can develop when people feel they have no real say in the planning process. Potentially this plays a role especially in rural areas if people choose to live there because of tranquillity; for them the wind farm can form an important threat (visual and auditory). Moreover, there is anecdotal report of growing polarization between groups of residents which influences individual positions and choices.

3.5.4 Noise sensitivity

Noise sensitivity refers to an internal state (physiological, psychological, attitude, lifestyle and activities) of a person that increases the reactivity to sound in general. Noise sensitivity has a strong genetic component (i.e. is hereditary), but can also be a consequence of an illness (e.g. migraine) or trauma. Also, serious anxiety disorders can go together with an extreme sensitivity to sound which can in turn increase a feeling of panic.[33]

Only a few studies have addressed this issue in relation to wind turbine sound. An early example is a study in New Zealand, in which two groups were compared (a ‘turbine group’ versus a control group).[34] Noise sensitivity was measured with a single question informing whether people considered themselves as noise sensitive. In the turbine group a strong association was found between noise sensitivity and annoyance and a weak association in the control group. This shows there may be an interaction between exposure and sensitivity that has an effect on annoyance. This has also been documented for other sound sources.[35] According to a case report from Thorne (2014), a relatively high proportion of residents near two wind farms in Australia were noise sensitive. Self-selection into a “quiet area” by noise sensitive people can be a plausible explanation. Recent studies of Michaud et al[20] and Kageyama[37] confirm the independent role noise sensitivity has on the reaction to wind turbines (see Chapter 4).

3.5.5 Social aspects

For the social acceptance of wind turbine projects by a local community the SHC stated it is crucial how the community evaluates the consequences for their future quality of life.[13] The communication and relation between the key parties (residents, municipality, project developer) is very important. Disturbance by wind turbines is a complex problem, in which the objective (physical) exposure and personal factors play a role, but also policy, psychology, communication and a feeling of justice.

When planning and participation are experienced as unjust or inadequate, public support will soon deteriorate also among people who were originally neutral or in favour of the wind farm.[38] When residents feel they have been insufficiently heard, they feel powerless and experience a lack of control over their own environmental quality and quality of life. Worry or concern can be reduced by an open and honest procedure in which residents can contribute to the decisions in a positive way.[39] Already in the early phase of wind energy, research from Wolsink[40] and later from Breukers[41] showed that collaboration with emphasis on local topics was more successful than a policy aimed at as much wind energy as possible and a non-participatory approach. According to Chapman et al[42] and Crichton et al[43] there is a strong psychogenic component in the relation between wind turbine sound and health complaints. This is not unique for wind turbine sound but has been documented for other sources as well (see e.g. [44,45,46]).

Many researchers have investigated the social acceptance of wind projects in a number of countries, including Switzerland, by local communities and many stress the relevance of a fair planning process and local involvement.[47-50,133]

4. WIND TURBINE SOUND and HEALTH

This chapter summarizes the state of the art regarding the knowledge available about the association between wind turbine sound and health. It is based on several literature searches and systematic reviews recently performed in the Netherlands.[51,52] Using the same search method (see annex A for full description), these searches were updated with literature until February 2017. Some papers from the most recent conference on Wind Turbine Noise (May 2017) have been added.

After a short explanation of the health effects addressed in the literature, first the main findings regarding noise annoyance, sleep disturbance and other health effects described in key reviews published until early 2017 are summarized. The influence of personal, situational and contextual factors on these effects is also included. Then, the most recent studies (2015-2017) will be described separately in more detail. These studies do not appear in reviews yet but are of high value as they build on earlier studies. The review is primarily based on results from epidemiological studies at population level, and smaller scale laboratory experiments. In addition, examples of individual stories are given, since they can enhance our insight in the problems that people living near wind turbines can experience.

4.1 Which effects have been studied?

People can experience annoyance from wind turbine sound, or irritation, anger or ill-being when they feel that their environmental quality and quality of life deteriorates due to the siting of wind turbines near their homes. This can lead to long term health effects. Annoyance and sleep disturbance are the most frequently studied health effects of wind turbine sound as is also the case for sound from other sources. In line with the World Health Organization's (WHO) definition[53] of health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity", noise annoyance and sleep disturbance are considered as health effects.[54,55]

4.1.1 Overview of the effects studied and mediating factors

The number of publications on wind turbine sound and its health effects has increased considerably in the past ten years, including peer reviewed articles, conference papers and policy documents. They include [19,56-62,134] and papers from the Internoise and Wind Turbine Noise conferences in the years 2011-2014.

In the past years a large number of reviews was published. The number of experimental and epidemiological studies was limited but recently has been increasing. Recent and leading reviews and policy documents draw comparable conclusions about the health effects of wind turbine sound: in general, an association is found between the sound level due to wind turbines and annoyance from that sound. Also, an association with sleep disturbance is considered plausible, even though a direct relation is still uncertain because of the limited number of studies with sometimes contradictory results. Next to sound, vibration, shadow flicker, warning lights and other visual aspects have been examined in the reviews. Stress is related to chronic annoyance or to the feeling that environmental quality and quality of life has diminished due to the placement of wind turbines, and there is sufficient evidence that stress can negatively affect people's health and well-being in people living in the vicinity of wind turbines.[13] The literature is inconclusive about the influence of low frequency sound and infrasound on health. There are no studies available yet about the long-term health effects. Such longitudinal studies (studies comparing the situation at different times) would be more suitable to gain insight in the causality of the different factors.

Most recently, Onakpoya et al[61] reanalysed the data from eight cross sectional studies, selected on strict quality requirements and including 2433 participants. Effects considered were annoyance, sleep disturbance and quality of life. Evidence supports the earlier conclusion that there is an association between exposure to wind turbine sound level and an increased frequency of annoyance and sleep problems, after adjustment for key variables as visual aspects, attitudes and background sound levels. The strength of evidence was the most convincing for annoyance followed by sleep disturbance, comparing effects at exposure levels below and above 40 dBA. The findings are in line with Schmidt and Klokker[62] and Janssen et al[63], but not with Merlin et al[19] who concluded that the direct effect of wind turbine sound on annoyance was weak and annoyance was more strongly related to other (contextual) factors.

The review of Harrison[60] is primarily focused on the health effects of low frequency sound and will therefore be discussed in Chapter 5.

As stated in Chapter 3 personal and contextual factors can influence annoyance. There is consensus in the literature that visual aspects, attitudes towards wind turbines in the landscape and towards the people responsible for wind farms, the process around planning and construction and economic interest can all in their own way affect levels of annoyance.

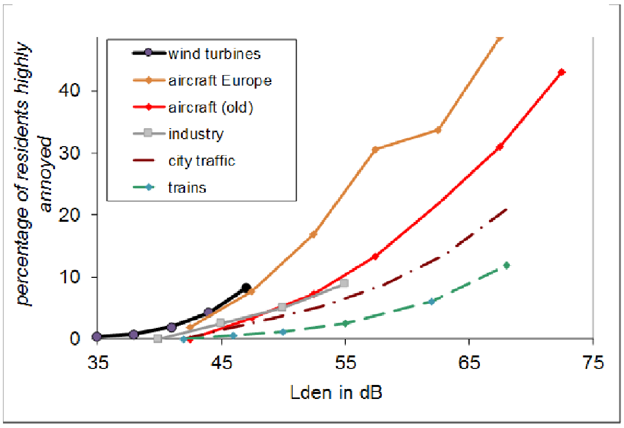
The next sections will describe the state of the art in more detail per health effect. Note that the description is limited to the effects of wind turbine sound in general in the "normal" frequency range. Findings from studies, addressing specific impacts of the low frequency component and infrasound distinct from "normal" sound are summarized separately in Chapter 5.

4.2 Noise annoyance

In many countries the assessment of the sound of wind turbines is based on average, A-weighted sound levels (see Chapter 2). It is generally accepted that annoyance from wind turbines occurs at lower levels than is the case for transport or industrial sound. Based on Dutch and Swedish data an exposure-effect relation was derived between calculated sound exposure levels expressed in Lden and the percentage highly annoyed, for in as well as outdoor exposures. Later research in Poland[64] and Japan[65] have confirmed these results and obtained comparable results. The relation between wind turbine sound level and annoyance can be compared with those for road, rail, aircraft and industry. This comparison is presented in figure 2 where the wind turbine data are from Janssen et al[63], the 'aircraft Europe' data from the European HYENA study[66] and the other data from Miedema and Vos[67] for industrial sound and from Miedema and Oudshoorn[68] for air, road and rail transportation sound. The more recent HYENA study has shown that at a number of big European airports noise annoyance has increased when compared to the older data from Miedema and Oudshoorn[68]. Figure 2 shows that sound from wind turbines leads to a higher percentage of highly annoyed when compared to other sound sources. The relation resembles that of air traffic sound, but near airports there are higher sound levels and a correspondingly higher percentage of highly annoyed. The relations for transport sound in figure 2 have been derived for large numbers of persons from many countries, but the actual percentage for a specific place or situation can be very different, for wind turbines as well as other sources.

Some think that it is too early to define exposure-effect relations for wind turbines.[13,69] According to them, the influence of context (like residential factors, trust in authorities and the planning process, situational) and personal factors (such as noise sensitivity and attitudes) is so strong that the exposure-effect relation can only (or at best) give

Figure 2: Comparison of the percentage highly annoyed residents from sound of wind turbines, transportation and industry (approach adapted from Janssen et al[63])



an indication of the percentage of highly annoyed at the local level.[19,59] This is not unique to wind turbines, but is - to some degree - also true for other sound sources and in part explains why in specific places or situations the actual percentage of annoyed persons can differ from the relations in figure 2. Michaud et al[20] compared the results from five studies and found there was a 7.5 dB variation in wind turbine sound levels that led to the same percentage of annoyed persons.

What makes wind turbine sound so annoying?
In a Dutch survey[30] performed in 2007 75% of the respondents indicated that the terms "swishing/lashing" gave the best description of wind turbine sound, irrespective of their being annoyed or not by the sound. Laboratory studies have shown since a long time that the periodic variation in the sound of wind turbines adds to the annoyance. Already in 2002 annoying wind turbine sound was described as 'swishing', 'lapping' or 'whistling' and the least annoying as 'grinding' and 'low frequency'.[70] In the UK research was performed near three dwellings where people complained about wind turbine sound.[71] Rather than the low frequency component of the sound, amplitude modulation or the rhythmic character was stated to be the most conspicuous aspect of the sound. In a later UK study Large and Stigwood[132] concluded that amplitude modulation is an important aspect of the intrusiveness of wind turbine sound. More recently Yoon et al[72] stated that there is a strong possibility that amplitude modulation is the main reason why wind turbine sound is easily detectable and relatively annoying.

Whether the type of environment affects the levels of wind turbine annoyance is not yet clear. It can be assumed that people in rural areas are more likely to hear and see wind turbines than in more built up urban areas with more buildings and a less open view. However, Dutch research showed that the percentage of highly annoyed people was equally high in rural and urban areas,[30] although the correlation with the wind turbine sound level was less strong in the built-up area.[73] Only in rural areas the presence of a nearby busy road led to a reduction of the percentage annoyed residents by wind turbine sound. In a Swedish study it was found that residents in rural areas reported more annoyance in rural areas than in urban environments, possibly due to their expectation that the rural area would be quiet.[31].

The findings regarding low frequency sound and infrasound are not easy to interpret. It may be confusing that the frequency of the rhythmic changes in sound due to amplitude modulation is the same as the frequency of an infrasound component. Also, some authors conclude that low frequency sound and infrasound may play a role in the reactions to wind turbine sound that is different from the effects of 'normal' sound,[74,75] though this is contested by many others. This topic is discussed in Chapter 5.

4.3 Sleep disturbance

Good sleep is essential for physical and mental health. Sound is one of the factors that can disturb sleep or affect the quality of sleep. Several biological reactions to night time sound are possible: increased heart rate, waking up, difficulty in falling asleep, and more body movements (motility) during sleep.[55] A Dutch study found that wind turbine sound did not affect self-reported sleep onset latency but did negatively influence the ability to keep sleeping.[30,73] An increase in outdoor residential sound level above 45 dBA increased the probability of awakening. This was not the case for people who obtained economic benefit from the wind turbines, but this might also have been an age effect (co-owners of the turbines were younger). These findings of the study in the Netherlands are in line with the conclusions which the WHO drew from a review of scientific literature on the relation between transportation noise and sleep (Night Noise Guidelines[55]). According to the WHO, sleep disturbance can occur at an average noise level due to transport noise at the façade at night (Lnight) of 40 dB and higher. This is similar to conclusions of research into the relation between wind turbine sound and sleep in the reviews mentioned above. The night noise guidelines of the WHO are not specifically and exclusively aimed at noise from wind turbines but cover a whole range of noise sources. It is conceivable that the relatively small sound peaks just above the threshold for sleep disturbance due to the rhythmic character of wind turbine sound cause sleep disturbance.[76]

A direct association between wind turbine sound and sleep disturbance can only be concluded on when there is a measurable reaction to the sound. Such an immediate influence is only plausible when the sound level is sufficiently high and as yet has not been convincingly shown for wind turbine sound.[19, 57,59] An indirect effect has been shown between self-reported sleep disturbance and annoyance from wind turbine sound, but not between sleep disturbance and the sound levels per se.[73] Research has shown that also for other sound sources there is a high correlation between self-reported sleep disturbance and annoyance from noise.[77]

Several more recent studies show an association between quality of life and sleep disturbance and the distance of a dwelling to a wind turbine.[78,79] Differences in perceived quality of life were associated with annoyance and self-reported sleep disturbance in residents. These results are highly comparable with those found for air and road traffic (e.g. see [80]).

4.4 Other health effects due to sound

In an Australian report[36] the number of people living in the vicinity of wind turbines with serious health complaints was estimated to be 10-15%. However, literature reviews on the health effects of wind turbines[13,19,56,57,58,59,61,62] conclude differently. According to these reviews there is no evidence for health effects caused by wind turbines in people living in the vicinity of wind turbines, other than annoyance and self-reported sleep disturbance and the latter inconclusive. There is however a correlation between annoyance and self-reported sleep disturbance[73] and perhaps other effects.[19] Based on existing field studies there is insufficient evidence that living near a wind turbine is the direct cause of health effects such as mental health problems, headaches, pain, stiffness, or diseases such as diabetes, cardiovascular disease, tinnitus and hearing damage.

4.5 Influence of situational and personal factors

Research in the past years has shed some light on why some people are more disturbed by sound from wind turbines than others. Apart from the typical rhythmic character of the sound, visual aspects contribute considerably to the negative reactions to wind turbines. These characteristics are often described as ‘intrusive’: especially the swishing sound, the varying flicker and the continuous movement of the blades.[18] Also, the diminishing level of road traffic sound at night while a wind turbine sound level remains the same or even increases at night might affect people’s perceptions. People who can see the turbine from their dwelling might report more annoyance because they fear that the turbine will damage their health.[13]

Personal and situational factors can play a role in annoyance from wind turbines. From the literature a broad range of factors emerges which has been shown to influence annoyance: economic interest, procedural fairness, unpredictability of the sound due to weather conditions, fear for accidents, attitudes towards the visual aspects, noise sensitivity, social acceptance, and the feeling that privacy is intruded, to name a few. Individual reactions vary accordingly. There is a lot of variation in the aspects studied and also the strength of the evidence varies strongly. Recently more attention was given to the influence of expectations on the level of annoyance[42,43] and the level of awareness (‘notice’) of the characteristics and prominent sounds of wind turbines.[82] The influence of all these factors is not unique for wind turbine sound but has been found in many studied regarding the effects of sound sources.[78]

4.6 Evidence since 2015

4.6.1 Health studies

In the period between January 2015 and 2017 21 relevant publications were identified in the peer reviewed literature. These are nine papers on field studies[20,37,82-88], seven on experiments[72,89,90-94], three on a prospective cohort study[95-97], one panel study[98] and one qualitative analysis of interviews and discourse.[99]

Two major studies were performed in this period, one in Canada[20,82-86] and one in Japan[37]. These are discussed in more detail in the next sections.

4.6.2 Health Canada study

The study from Health Canada[20,57,82-86] was performed among 1238 adult residents living at varying distances from wind turbines. A-weighted sound levels outdoors were calculated as well as C-weighted levels, and additional measurements were made at a number of locations. A strong point of the study is the high response rate of 79 percent. The results were presented in six publications, addressing effects on sleep, stress, quality of life, noise annoyance and health effects and a separate paper on the effect of shadow flicker on annoyance. Also, two papers were published describing the assessment of sound levels near wind turbines and near receivers.[100,101]

In one of these papers[82] Michaud et al describe the findings on annoyance, self-reported health and medication use. In line with earlier findings the study confirms that the percentage of residents highly annoyed with wind turbines increased significantly with increasing wind turbine sound levels. The effect was highest for visual impact of wind turbines, followed by blinking lights, shadow flicker, sound and vibrations. Beyond annoyance, results do not support an association between exposure to wind turbine sound level (up to 46 dBA) and the evaluated health-related endpoints such as mental health problems, headaches, pain, stiffness, or diseases such as diabetes, cardiovascular disease, tinnitus and hearing damage.

The paper of Voicescu et al[85] on the same data set studied the effect of shadow flicker, expressed as the maximum duration in minutes per day, in combination with sound levels and distance, on annoyance and health complaints including dizziness. As shadow flicker exposure increased, the percentage of highly annoyed increased from 4% at short duration of shadow flicker (<10 minutes) to 21% at 30 minutes of shadow flicker. Variables associated with the percentage highly annoyed due to shadow flicker included concern for physical safety and noise sensitivity. Reported dizziness was also found to be significantly associated with shadow flicker.

In a further paper, of Feder et al[86], results for quality of life (Qol) showed no effect at sound levels up to 46 dB. QoL was measured using the WHO Qol index that includes physical, environmental, social quality and satisfaction with health. This appears to be in contrast with findings reported earlier by Shepherd et al[78] and Nissenbaum et al[79], who did find significant effects of distance on QoL. However, the results of these studies are hard to compare because the exposures are not the same (sound level or distance) and because different instruments were used to measure perceived quality of life. Important moderating variables in the Canadian study were economic benefit and annoyance from visual aspects of the turbines. These variables have been reported earlier by many other researchers as far as noise annoyance is concerned.[31,32,102-104] In all these studies, being highly noise sensitive was also related to more annoyance. Similarly, the odds of reporting poor QoL and dissatisfaction with health were higher among those who were highly noise sensitive. However, after adjustment for current health status and work situation (unemployment) the influence of noise sensitivity became marginal.

Michaud et al[83] reported on sleep disturbance from a field study involving 742 of the 1238 respondents wearing an actimeter, to measure several relevant sleep quality indicators during 3-7 consecutive nights after the interviews. Outdoor wind turbine sound levels were calculated following international standards for conditions that typically approximate the highest long-term average levels at each dwelling. Neither self-reported sleep quality, diagnosed sleep disorders nor objective measures such as sleep onset latency, awakenings and sleep efficiency showed an immediate association with exposure levels up to 46 dB (after adjustment for relevant confounders such as age, caffeine use, BMI and health condition). This partly contrasts with earlier findings on subjective sleep measures.[31] No other study addressed objective sleep measure before, so comparisons can only partly be made. The method of actigraphy is limited as compared to more elaborate polysomnographic measures as were employed by Jalali et al[96] and described below (section 4.6.7).

Michaud et al also studied the association between wind turbine sound level and objective stress indicators (cortisol, heart rate) and perceived stress (PPS index).[84] The several stress indicators were weakly associated with each other, but analysis showed no significant association between exposure to wind turbine sound levels (up to 46 dBA) and self-reported or objective measures of stress. McCunney et al[56] also did not find a significant association and the explanation was that sound levels from wind turbines do not reach levels to cause such direct effects. Bakker et al did find an association between sound level and psychological distress, but the actual association was shown to be between noise annoyance and distress.[73]

Finally, the role of personal and situational aspects was studied using the Health Canada data.[20] Fear and concern about the potential harm of wind turbines showed to be an important predictor of annoyance as has been reported earlier for other noise sources.[45,105-107] Noise sensitivity was also a strong and independent predictor of annoyance. Having to close the window in order to guarantee an undisturbed sleep had by far the strongest influence on annoyance. This could be a reason that no relation between wind turbine sound level and sleep disturbance was found: if persons disturbed at night by wind turbine sound would close their bedroom window, the result could be that they are less disturbed at night, although they could be annoyed because they had to close the window. The results do not directly support or negate this explanation. However, those closing their bedroom windows were eight times more likely to be annoyed. Elsewhere it is mentioned that at higher wind turbine sound levels people more often reported wind turbines as a reason for closing the bedroom window.[82]

Personal benefit from wind turbines was associated with reduced annoyance, in a significant but modest way as was found by others.[29] Length of exposure seemed to be an important situational factor and led up to 4 times higher levels of annoyance for people living more than one year in the vicinity of a wind turbine, indication a sensitization to the sound rather than adaptation or habituation as is often assumed. The Canadian results show that the moderate effect of wind turbine sound level on annoyance and the range of (other) factors that predict the level of annoyance implies that efforts aimed at mitigating the community response to wind turbine sound will profit from considering other factors associated with annoyance.

4.6.3 Japan study

Kageyama et al report on a field study in Japan with structured face to face interviews at 34 study sites (with wind turbines) and 16 control sites (no turbines).[37] Wind turbine sound levels were estimated based on previous measurements at some sites and expressed as average sound levels (L_{Aeq}). Outcomes studied were sleep deprivation, sleep disturbance, and physical and mental health symptoms. Analysis showed a significant association between sound levels above 40 dB and sleeping problems (insomnia). Self-reported noise sensitivity and visual annoyance with wind turbines were independently associated with insomnia.

These findings are in contrast with those reported by Michaud et al[83] who did not observe an immediate association between sound exposure levels and subjective and objective indicators for sleep. The earlier findings of Bakker et al regarding subjective sleep indicators showed that sleep disturbance seemed to be related to sound level only when no others factors were included.[73] When annoyance with wind turbine sound was included, then sleep disturbance was related to that annoyance and not anymore to sound level. Earlier, Pedersen and Persson Waye also concluded on an association between annoyance and sleep disturbance rather than a direct effect with sound levels.[31]

In the Japanese study poor subjective health was not related to wind turbine sound level, but again noise sensitivity and visual annoyance were significant predictors for the effects studied. Both noise sensitivity and visual annoyance seem to be indicators of a certain vulnerability to environmental stimuli or changes in environmental factors.

In a later publication from the Japanese study it was found that within 860 m from a wind farm 10% of the residents were annoyed by shadow flicker while within 780 m 10% of the residents were highly annoyed by wind turbine noise.[108] The authors concluded that a minimum (or 'setback') distance between residences and wind farms should be considered from an aural and visual point of view.

4.6.4 Other field studies

In the period between January 2015 and February 2017 two smaller studies have been reported from Denmark[88] and Iran[87]. Starting with the first, a survey was held among 454 citizens living in rural areas at varying distances to wind turbine farms with a varying numbers of wind turbines. The study included idiopathic symptoms (i.e. not related to a specific disease) as effects and distance to the wind farm and the number of turbines as a measure of exposure. An association of distance with fatigue, headaches and concentration problems all disappeared after adjustment for exposure to sound and odour from other sources.

The Iranian study of Abassi et al did not include residents, but 53 workers divided in three groups with repairing, security and administration tasks.[87] The exposure to wind turbine sound of employees in each job group was measured as an eight-hour equivalent sound level as is usual in working conditions. Outcome measures included annoyance, sleep, psychological distress and health complaints. Noise sensitivity, age, job stress and shift work were accounted for. Annoyance was associated with measured sound levels but lower than found in residential studies. The other health outcomes did not show a significant association. It is not clear how this relates to residential conditions as the situations are quite different and different factors are involved.

More recently, at the Wind Turbine Noise conference in May 2017, the first results were published of a new British study that was held near wind turbines in densely populated, suburban areas.[109] In this study part of the participants received a questionnaire that included explicit questions on the impacts of the local wind turbines on well-being, and the remaining part received a variant with no such questions. When including all participants, there was less annoyance from wind turbine noise in this study compared to what was found in the earlier (Swedish, Dutch, Polish and Canadian) studies in rural areas. For the first group (with questions concerning local wind turbines) the noise levels were not significantly related to health problems and this group reported less health problems and better general health; this was opposite to the relationship found in the other, variant group.

4.6.5 Laboratory studies

In the period 2015-2017 several laboratory studies have addressed the effects of wind turbine sound on annoyance. In a listening test among 60 people, after a pilot with 12 people, Schäffer et al[93] found an association between wind turbine sound and annoyance, but the annoyance levels were lower than those reported by Janssen et al[63] and Michaud et al[20]. Attitude towards wind turbines as well as noise sensitivity were important confounders, and finally the frequency seemed to play an important role.

The relative contribution of the typical characteristics of wind turbine sound, and especially the rhythmic character or amplitude modulation (AM) was studied in several experiments.

Ionannidou et al report on a study among 19 volunteers in which the effect of changes over time in the amplitude modulation of wind turbine sound on annoyance was investigated.[91] The changes could either be the frequency of the modulation, the depth (or strength) of the modulation, or a change in depth over time. The study confirms earlier results that AM leads to a higher annoyance rating. A higher modulation frequency (from 0.5 to 2 Hz) also resulted in a higher rating, but the effect was not significant. There was also a higher annoyance rating when the modulation depth increased intermittently, but again this was not significant. Because of the limited statistical power of this test (because of the low number of participants and the limited time), it was recommended to investigate the variations in AM for a longer period and in a field setting.

A study from Hafke-Dys et al among 21 volunteers again concerned the effect of amplitude modulation on annoyance.[90] In this study sounds with several modulation conditions were used. The test sounds used were 1) sound from moving cars, passing at a rate of 1 to 4 per second; 2) broadband sound with the same spectrum as wind turbines and 3) narrowband sound that could be modulated at 1, 2 and 4 Hz. All three types of sound had modulation depths typical for wind turbines at 3, 6 and 9 dB similar to Van Renterghem et al[81], or zero (no modulation). Results showed that AM did increase annoyance in the case of broadband sound and passing cars, but not for the narrow band sound. The modulated sound was more annoying with increasing modulation frequency, in agreement with an expected highest sensitivity for modulated sounds at 4 Hz. Modern wind turbines modulate their sound at a frequency close to 1 Hz. The effect of AM on annoyance was less for the broadband sound than for passing cars. The main difference between these two sounds was the spectral content, with the broadband sound having less low frequency sound than the passing cars. The authors conclude that this result supports the Japanese study[14] in which it was demonstrated "that low frequency components are not the most significant problem when it comes to the annoyance perception of wind turbine noise".

Yoon et al studied the reaction to modulation of wind turbine sound in 12 people.[72] Findings show again that there is an association between AM and level of annoyance. The authors conclude that there is a strong possibility that amplitude modulation is the main cause of two typical properties of wind turbine sound: that it is easily detectable and highly annoying at relatively lower sound levels than other noise sources. They add that this does not mean that these properties can be fully explained by the amplitude modulation.

Maffei et al studied 40 people subdivided in a group familiar for a long time with wind turbine sound versus a group not familiar with wind turbine sound.[92] The study comprised a listening test to sound recorded at a wind farm of 34 wind turbines including background sound (wind in vegetation), or only background sound. Sound recordings of about 5 minutes duration were made at five distances (150 up to 1500 m) from the wind farm. For each distance 65 soundtracks were used and characterized in terms of sound level and the main psychoacoustical indexes (loudness, fluctuation strength, sharpness, tonality and roughness). The aim was to detect wind turbine sound at varying distances. For both groups of participants, familiar and unfamiliar, there was no difference in recognition of wind turbine sound at distances of 300 m or less and detection was easiest at distances up to 250 m. At 1500 m those familiar with wind turbine sound could detect the sound better, but they also reported more often 'false alarms'. Noise sensitivity was an important factor.

In two studies the role of expectations was investigated. Crichton et al[89] studied 60 volunteers at exposure levels up to 43 dBA (the New Zealand standard limit) in combination with infrasound (9 Hz, 50 dB). In one group the participants were shown a video about the health risk of wind turbine infrasound, in the second group a video on health benefits was shown. An effect on annoyance was found only in the group expecting to be negatively affected and in this group noise sensitivity increased the likelihood of being annoyed. In the group expecting a positive effect there was far less annoyance and almost no influence from noise sensitivity.

Tonin et al[94] studied 72 volunteers in a laboratory setting for a double-blind test similar to that of Crichton et al[89] but used infrasound at a higher level (91 dB). Before the listening test, participants were influenced to a high expectancy of negative effects from infrasound with a video of a wind farm affected couple, or a low expectancy of negative effects with a video of an academic explaining why infrasound is not a problem. Then normal wind turbine sound was presented via a headset to all participants with the inclusion of the infrasound or no infrasound for a period of 23 minutes. The infrasound had no statistically significant effect on the symptoms reported by participants, but the concern they had about the effect of infrasound had a statistically significant influence on the symptoms reported.

4.6.6 Other studies

Jalali et al report on a prospective cohort (i.e. before - after) study with 43 participants who completed a questionnaire in spring 2014 and again a year later.[95] Exposure to a wind farm was only measured in terms of distance. Residents who were annoyed by the sound or sight of turbines, or who had a negative attitude towards them or were concerned about property devaluation, after one year experienced lower mental health and quality of life, and reported more symptoms than residents who were not annoyed and had positive attitudes toward turbines. The response rate for this study was low (only 22%) and 12 people (of 43 that's is approximately 25%) were not in the second round. Another weak point is the lack of a control group.

By the same authors, sleep disturbance was measured in a group of 16 people for 2 consecutive nights.[96] A polysomnographic method was used, including a range of sleep and physiological parameters such as sleep onset, duration, movement during sleep, awakening, EEG activity, etc. Sound measurements over the whole frequency range (0.5 to 20.000 Hz) were performed in the bedroom as well as outdoors, while accounting for weather conditions, wind speed and temperature. Factors that were taken into account were attitude, sensitivity, visibility, distance within 1000 meters and windows open versus closed. Results showed no major changes in the sleep of participants who had new wind turbines in their community. There were no significant changes in the average indoor (31 dBA) and outdoor sound levels (40-45 dBA before, 38-42 dBA after) before and after the wind turbines became operational. None of the participants reported waking up to close their windows because of the outside noise. The lack of an effect might be explained by the limited measurements (two nights) or the low indoor noise levels that almost equalled the threshold value for sleep disturbance of 30 dBA.

In a third paper Jalali et al report on the association between measured wind turbine sound levels and subjective sleep quality as measured with the Pittsburgh sleep quality index.[97] Results show only an indirect association with attitude towards the wind turbines, concern about reduced housing values and the visibility of the turbine from the properties. The results confirm the strong psychological component and individual differences where it concerns sleep disturbance from wind turbine sound.

Against the background of the increasing number of wind farms in Germany, Krekel et al (2016) investigated the effect of the presence of wind turbines on residential well-being.[98] This was done by combining household data from the German Socio-Economic Panel with a dataset on more than 20.000 wind turbines for the time period between 2000 and 2012. The key effect studied was life satisfaction. Results showed that the construction of one or more wind turbines in the neighbourhood of households had a significant negative effect on life satisfaction. This effect was limited both in distance and time.

Botterill and Cockfield[99] studied the discourse about wind turbines in submissions to public inquiries and in a small number of detailed interviews, and topics addressed in the discourse. Health and property values were found to be the most prominent topics discussed with regards to wind turbines (and aesthetics/landscape arguments less often) but in interviews were never mentioned.

4.7 Individual cases

Apart from the limited epidemiological studies concerning the health effects of wind turbine sound, personal narratives and case reports can enhance our insight of (sound from) wind turbines. The nuance and personal differences often drown in the statistics. Also in surveys an effect can be missed because it was not included in the questionnaire or the effect is so rare that it disappears.

In the literature a few examples have been found where individual cases ('case studies') were analysed in a systematic manner (e.g. [18,110,111]). People who object to this method often state that only negative cases are presented. On the other hand, such an analysis can add to our understanding what exactly has triggered and maintained negative reactions. According to some, the extent, consistency and uniformity of symptoms described in case studies can be considered as preliminary epidemiological evidence for an association between wind turbine sound and sleep disturbance or other health effects.[111]

Based on the case studies the following set of indicators is mentioned more often:

1. Distance to the turbine;
2. Character of the wind turbine sound;
3. The way residents were treated during the planning and construction process;
4. Health problems;
5. Sleep issues and accompanying problems.

4.7.1 Summary of three cases from the USA

The three cases described first are from Philips.[111]

The first case concerns a man with three children. The wind turbines were placed one by one in the course of time and the closest turbine is within 330 m from the dwelling. He describes the turbine sound as loud and comparable with aircraft sound." It is a 'woosh' sound and it creaks, grinds and bangs". The sound is all around us and it goes in all directions. It resembles an angry thing above you which does not allow for any tranquillity. The noise prevents you from thinking and the body is not capable to adapt to it". His children suffer from sleep problems and have consequential problems at school. Eventually the family moved and the home was not saleable.

The second case concerns a woman and her son. Within 3 km from her dwelling 16 turbines were placed, the nearest one at 400 meters. She describes the sound as continuous with daily fluctuations. There is no way to escape from the sound. In particular the shadows and flickers through the window are irritating and she has developed a hypersensitivity to motion (e.g. the ventilator on the ceiling). Also, she developed tinnitus and a pulsating feeling in neck and chest. Other complaints are nausea, vertigo, hearing loss, itchy eyes, high blood pressure, memory problems, headaches, palpitations, painful joints and sleeping problems: a sleep test showed 214 "disturbances" in six hours. The housing values in the area have dropped considerably and the woman often resorts to friends where they immediately fall asleep. She indicates to be angry and feels powerless and she is very disappointed and feels badly understood by the government.

The third case is a man who lives within 500 meter from a wind turbine. He experiences reduced quality of life. His complaints are fear, nervousness sleep problems, hypertension, tension, migraine, vertigo, bad vision, palpitation, anger, stomach problems and depression. He indicates that it is not about loudness but rather about the typical characteristics of wind turbine sound: It settles in "your head" and you wait for it when it is not there. He indicates that it is not possible anymore to sit in the garden and he uses the term 'turbine torture'. After being away for a month the complaints were gone but started again when he returned. The number of buyers of dwellings in the area have reduced with 50%.

4.7.2 A case from the Netherlands

In the Netherlands, comparable reactions have been reported as is shown on the online complaint site (windmolenklachten.nl) and other sites. One example is:[52]

"A few years the wind turbine is there, a gigantic wind turbine just behind our house. As an advocate of sustainable energy I originally have tried to take a positive stand but this has gradually disappeared and changed into a true dislike in the sick making monster. With certain directions of the wind with a force of 4 to 5 it sounds as if a whole range of military aircrafts take off from our garden. No sleep and the annoyance is getting at you. We cannot take more of this, it is subsidized terror. Time for action."

4.7.3 Analysis of non-selected perceptions in Sweden

In a Swedish study by Pedersen et al[18] 15 interviews were held with people selected from a group of residents with varying levels of annoyance due to wind turbine sound. The information from these interviews has been systematically analysed. The interviewees described the wind turbines as intrusive and as disturbing their privacy. This was primarily related to the idea that the sound and visual aspects did not match their living environment. Also, it was judged as important that the authorities did not take them seriously and they felt treated in an unfair manner. The lack of control and a voice created a feeling of being powerless. Several strategies were used, with varying results, to cope with this such as filing a complaint, covering the verandas and trying to ignore the sound

6. HEALTH EFFECTS SPECIFIC for LOW FREQUENCY SOUND and INFRASOUND

In the non-scientific literature, which can be found on the internet, a range of health effects are attributed to the presence of wind turbines. Infrasound is described as an important cause of these effects, also when the (infra)sound levels must be very low or are unknown. In this chapter the question is whether infrasound or low frequency sound deserves special consideration with respect to the effects of wind turbine sound. There is some discrepancy when comparing conclusions from the majority of scientific publications to conclusions in popular publications. Also, some scientific publications suggest possible impacts that are not generally supported.

First, we will consider the audibility of infrasound and low frequency sound, then possible health effects not involving audibility.

5.1 Audibility of infrasound and low frequency sound

Audible low frequency sound is all around us, e.g. in road and air traffic. Audible infrasound is less ubiquitous, but can be heard from big machines and storms. In most publications on wind turbine sound there is agreement that infrasound and low frequency sound are present in wind turbine sound. Generally, it is acknowledged that infrasound is inaudible as infrasound levels are low with respect to human sensitivity (e.g. [12,19,112,113]).

Even close to a wind turbine, most authors argue that infrasound is not a problem with modern wind turbines. This can be shown from measurement results at 10 and 20 Hz. At the (infrasound) frequency of 10 Hz the A-weighted sound power level is typically 60 dB lower than the total sound level in dBA.[16] At a receiver with a total sound level of 45 dBA this means that the 10 Hz sound level is about minus 15 dBA or, in physical terms (not A-weighted), 55 dB. This is far below the hearing threshold at that frequency, which for normal-hearing persons is about 95 dB. A sound of 55 dB at 10 Hz would also be inaudible for the few persons that have been reported with a much lower hearing threshold (close to 80 dB)[12]. At 20 Hz, the upper frequency limit of infrasound, the result, again at a receiver total sound level of 45 dBA, would be a physical level of wind turbine sound of 50-55 dB which is much lower than the normal hearing threshold at that frequency of 80 dB.

As part of a Japanese study on wind turbine low frequency sound, persons in a laboratory were subjected to wind turbine sound where very low frequencies were filtered out over different frequency ranges.[14] When infrasound frequencies were filtered out, the study persons did not note different sensations. Above about 30 Hz they began to notice a difference between the filtered and original sound.

Leventhall states that the human body produces infrasound internally (through blood flow, heartbeat and breathing, etc.) and this masks infrasound from outside sources when this sound is below the hearing threshold.[114]

In contrast to infrasound, there is general agreement that low frequency sound is part of the audible sound of wind turbines and therefore contributes to the effects caused by wind turbine sound. The loudest part of the sound as radiated by a turbine is in the mid-frequency range (250-1600 Hz)[16,17]. This shifts to lower frequencies when the sound travels through the atmosphere and enters a building because absorption by the atmosphere and a building façade reduces low frequencies less than higher frequencies. However, studying the effects of the low frequencies separately from the higher frequencies is not easy as both frequency ranges automatically go together: wind turbines all have very much the same sound composition. In a Canadian study on wind turbines the sound levels at the facades of dwellings were calculated both as A- and C-weighted sound levels, but this proved not to be an advantage as the two were so closely linked that there was no added value in using both.[100] A limit in A-weighted decibels (where the A-weighting mimics human hearing at moderate sound levels) thus automatically limits the low frequency part of the sound.[112] However, this may not be true when the character of wind turbine sound changes because of noise reduction measures.

Bolin et al[115] calculated and compared wind turbine and road traffic sound over a broad frequency range (0-2000 Hz) at sound levels considered acceptable in planning guidelines (40 dB L_{Aeq} for wind turbine sound and 55 dB L_{Aeq} for road traffic sound). Compared to road traffic sound, wind turbine sound had lower levels at low frequencies. Thus, at levels often found in urban residential areas, low frequency sound from wind turbines is less loud than from road traffic sound. Recent measurements in dwellings and residential areas show that similar levels of infrasound occur, when comparing wind turbine sound with sound from traffic or household appliances.[116]

5.2 Effect of lower frequencies

McCunney et al mention that both infrasound and low frequency sound have been suggested to pose possibly unique health hazards associated with wind turbine operations.[56] From their review of the literature, including results from field measurements of wind turbine sound and experimental studies in which people have been purposely exposed to infrasound, they conclude that there is no scientific evidence to support the hypothesis that wind turbine infrasound and low frequency sound has effects that other sources do not have.

5.3 Subaudible effects

The term ‘subaudible’ means that the level of a sound is below the hearing threshold and thus below the level it can be audible. Usually the ‘normal’ threshold (hearing threshold of young adults without hearing problems, according to the international standard ISO 326) is used. The normal threshold is the hearing threshold separating the 50% best hearing from the 50% that hear less well. There is variation between individuals, but for an individual often the normal hearing threshold is taken as an indication, though for that person of course the individual hearing threshold is relevant.

Several authors have linked infrasound and low frequency sound from wind turbines to health effects experienced by residents, assuming that infrasound can have physiological effects at levels below the (normal) hearing threshold.[110,117,118] This was supported by Salt and Kaltenbach[119] who argued that normal hearing is the result of inner hair cells in the inner ear producing electric signals to the brain in response to sound received by the ear. However, infrasound and low frequency sound (up to 100 Hz) can also lead to signals from the Outer Hair Cells (OHC) and the threshold for this is lower than for the inner hair cells. This means that inaudible levels of infrasound and low frequency sound can still evoke a response.[119] The OHC threshold is 60 dB at 10 Hz and 48 dB at 20 Hz. Comparing this to actual sound levels (see second paragraph of section 5.1) shows that infrasound levels from wind turbines could just exceed this OHC threshold when their total outdoor sound level is 45 dBA. It is unlikely that the OHC threshold can be exceeded indoors, where levels are lower, except at a high sound level that may occur very close to a wind turbine. Salt and Kaltenbach conclude from this that it is 'scientifically possible' that infrasound from wind turbines thus could affect people living nearby.[119] However, it is not clear to what reactions these signals would lead or if they could be detrimental when just exceeding the OHC threshold. If such inaudible sound could have effects, it is not clear why this has never been observed with everyday sources (other than wind turbines) that produce infrasound and low frequency sound such as road and air traffic. Or with physiological sounds from heart beat, blood flow, etc. However, high infrasound levels may be inaudible but can add energy to the rhythmic 'normal' sound of a wind turbine and thus make vibrations perhaps more likely (see section 5.5).

Farboud et al[120] conclude that physiological effects from infrasound and low frequency sound need to be better understood; it is impossible to state conclusively that exposure to wind turbine sound does *not* cause the symptoms described by authors such as Salt and Hullar or Pierpont.

Leventhall[114] argues that infrasound at low level is not known to have an effect. Normal pressure variations inside the body (from heart beat and breathing) cause infrasound levels in the inner ear that are greater than the levels from wind turbines. From exposure to high levels of infrasound, such as in rocket launches and associated laboratory studies or from natural infrasound sources, there is no evidence that infrasound at levels of 120 – 130 dB causes physical damage to humans, although the exposure may be unpleasant.[114]

Stead et al come to a similar conclusion when considering the regular pressure changes at the ear when a person is walking at a steady pace.[121] The up and down movement of the head implies a slight change in atmospheric pressure that corresponds to pressure 'sound' levels in the order of 75 dB. The pressure changes in the rhythm of the walking frequency are similar in frequency (close to 1 Hz) and level to the pressure changes from infrasound at rotation frequencies measured at houses near wind farms.

5.4 Vestibular effects

According to Pierpont the (infra)sound of wind turbines can cause Visceral Vibratory Vestibular Disease (VVVD), affecting the vestibular system from which we derive our sense of balance.[110] She characterized this new disease with the following symptoms: "a feeling of internal pulsation, quivering or jitteriness, and it is accompanied by nervousness, anxiety, fear, a compulsion to flee or check the environment for safety, nausea, chest tightness, and tachycardia", stating that infrasound and low frequency sound were causing this 'wind turbine syndrome'.[110] Pierpont's research was based on complaints from 38 people from 10 families who lived within 300-1500 meter from one or more turbines in the USA or Great Britain, Italy, Ireland and Canada. In several publications (e.g. [56,59]) it was pointed out that Pierpont's selection procedure was to find people who suffer the most, and it was not made clear that it was indeed the presence of the wind turbine(s) that caused these symptoms. Although the complaints may be genuine, it is possible that very sensitive people were selected and/or media coverage had lead to physical symptoms attributed to environmental exposures as has been demonstrated for wind turbines[42] and other environmental exposures[122]. Van den Berg noted that the symptoms of VVVD are mentioned in the Diagnostic and Statistical Manual of Mental Disorders (DSM) as stress symptoms in three disorders: an adjustment disorder, a panic disorder and a generalized anxiety disorder.[76] The Wind Turbine Syndrome or VVVD may thus not be a new phenomenon, but an expression of stress that people have and which could have a relation to their concern or annoyance with respect to a (planned) wind farm.

In his examination of the Wind Turbine Syndrome Harrison argued that at a level of 40–50 dBA no component of wind turbine sound approaches levels high enough to activate the vestibular system.[60] The threshold for this is about 110 dB for people without hearing ailments. In people with a hearing ailment, particularly the 'superior (semi-circular) canal dehiscence syndrome' (SCDS), this threshold is lower and can be 85 dB. Such levels are only reported very close to wind turbines. Reports show that 1 to 5% of the adult population may have (possibly undiagnosed) SCDS.

Schomer et al studied residents of three homes who generally did not hear the wind turbines in their area, but they did report symptoms comparable to motion sickness.[123] Schomer et al suggest that this could result from sound affecting the vestibular sensory cells and in their opinion wind turbine infrasound could generate a pressure that they compare with an acceleration exceeding the U.S. Navy's criteria for motion sickness. This has been investigated by Nussbaum and Reinis much earlier (1985).[124] They exposed sixty subjects to a tone of 8 Hz and 130 dB with high distortion (high level harmonics at multiples of 8 Hz) or low distortion (harmonics at lower level). Dizziness and nausea were primarily associated with the low distortion exposure, i.e. a relatively high infrasound content. In contrast, headache and fatigue was primarily associated with the high distortion exposure, with a relatively low infrasound content. Nussbaum and Reinis hypothesized that the effects of the purer infrasound could be explained as acoustically induced motion sickness. However, this was concluded from exposure levels (130 dB) much higher than wind turbines can cause.

5.4 Vibroacoustic Disease

According to Alves-Pereira and Castelo Branco the infrasound and low frequency sound of a wind turbine can cause Vibroacoustic Disease (VAD), an affliction identified by a thickening of the mitral valve (one of the valves in the heart) and the pericardium (a sac containing the heart).[117] The most important data regarding VAD are derived from a study among aircraft technicians who were professionally exposed to high levels of low frequency sound. VAD is controversial as a syndrome or disease. Results of animal studies have only been obtained in studies using low frequency sound levels which are found in industrial settings. No studies are known that use a properly selected control group. And finally the way the disease was diagnosed has been criticized because of a lack of precision.[125]

After investigating a family with wind turbines between 322 and 642 m from their dwelling, Castelo Branco et al concluded that VAD occurred and was caused by low frequency sound.[126] The measured sound levels were substantially lower (20 dB or more) than levels at which VAD was thought to occur by Marciniak et al[127] and the spectral levels were below the normal hearing threshold for a considerable range of frequencies in the low frequency range. In their review of evidence on VAD Chapman and St George concluded that in the scientific community VAD was only supported by the group who coined the term and there is no evidence that vibroacoustic disease is associated with or caused by wind turbines.[128]

5.5 Vibrations due to sound

In measurements at three dwellings Cooper found surges in ground vibration near wind turbines that were associated with wind gusts, outside as well as inside one of the three houses.[129] Vibration levels were weak (less than from people moving around), but measurable. According to Cooper two residents were clearly more sensitive than the other four; the sensations experienced by the residents seemed to be more related to a reaction to the operation of the wind turbines than to the sound or vibration of the wind turbines. This echoes earlier findings from Kelley et al who investigated complaints, from two residences, that were thought to be associated with strong low frequency sound pulses from the experimental downwind MOD-1 wind turbine.[130] The low frequency sound pulses were generated when a turbine blade passed the wind wake behind the mast. The residents perceived ‘audible and other sensations, including vibration and sensed pressure changes’. Although the wind turbine sound at frequencies below about 30 Hz was below the average hearing threshold, this sound was believed to be causing the annoyance complaints. The sound levels were within a range of sound levels and frequencies given by Hubbard for situations where (subaudible) industrial sound within this range was believed to be the source of the complaints. This could be explained by the response of a building to the sound outside, causing structure borne sound, standing waves and resonances due to the configuration of a room, closet and/or hallway. The rhythmic character of wind turbine sound could have an added effect because of the periodic pressure pulses; if these coincide with a structural resonance of the building the indoor level can be higher than expected from just reduction by the façade. These structural vibrations can lead to sound at higher frequencies which are audible. Several authors have pointed out that the rhythmic character itself (technically: Amplitude Modulation) is more relevant to human perception than low frequency or infrasound (see *What makes wind turbine sound so annoying?* in section 4.2 above). However, the appreciation of the sound may depend on a combination of the frequency and strength of the modulation and the balance of low and higher frequency components.[131]

7. CONCLUSIONS

Available scientific research does not provide a definite answer to the question whether wind turbine sound can cause health effects which are different from those of other sound sources. However, wind turbines do stand out because of their rhythmic character, both visually and aurally.

6.1 A graphic summary of the reaction to (planned) wind turbines.

There are many models or schemes that show how people react to noise. However, much of the public debate about wind turbines and noise is at a stage when wind turbines have not been erected yet. Michaud et al proposed a model that incorporated the influence of (media) information and expectations.[84] In figure 3 we present a simplified model based on the one from Michaud et al. The model shows that plans for wind turbines or actual wind turbines can lead to disturbances and concern, but a number of factors can influence the effect of the (planned) turbines (see the 'Michaud model' for these factors). The personal factors include attitude, expectations, noise sensitivity and many more. Situational factors include other possible impacts such as visibility or shadow flicker, other sound sources, type of area and others. Contextual factors include participation, the decision making process, the siting procedure, procedural justice and others.

6.2 Conclusions from chapter 3

Next to noise, several other features are relevant for residents living in the vicinity of wind turbines. These include physical and personal aspects, and the particular circumstances around decision making and siting of a wind farm as well as communication and the relation between different people involved in the process.

Visual aspects play a key role in reactions to wind turbines and include the (mis-) match with the landscape, shadow casting and blinking lights.

Shadow casting from wind turbines can be annoying for people and also the movement of the rotor blades themselves can be experienced as disturbing.

Light flicker from the blades, vibrations and electromagnetic fields play a minor role in modern turbines as far as the effect on residents is concerned.

People who benefit from and/or have a positive attitude towards wind turbines in their environment in general report less annoyance.

People who perceive wind turbines as intruding into their privacy and detrimental to the quality of their living environment in general report more annoyance.

Perceived (procedural) injustice has been found to be related with the feeling of intrusion and lack of control/helplessness.

Most studies confirm the role of noise sensitivity in the reaction to wind turbines, independent of the sound level or sound characteristics.

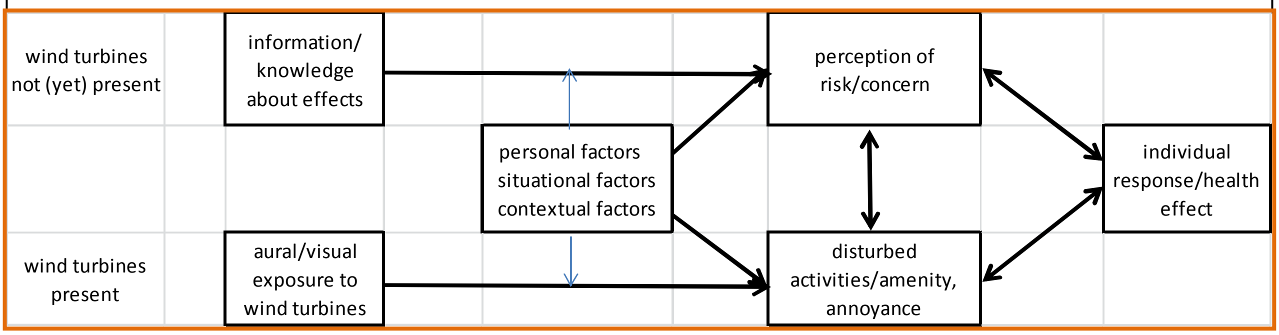
Attitude and media coverage are just a few elements of the complex process which plays a role in decision making for siting wind turbines. Most recent studies conclude that social acceptance of wind projects is highly dependent on a fair planning process and local involvement.

6.3 Conclusions from chapter 4

Noise annoyance is the main health effect associated with the exposure to noise from an operational wind turbine.

From epidemiological studies, experiments and individual narratives the typical character of wind turbine sound comes forward as one of the key issues.

Figure 3: a model for the relation between the exposure to (information about) wind turbines and the individual reaction



At equal sound levels, sound from wind turbines is experienced as more annoying than that of road or rail traffic or industrial sources. Residential wind turbine sound levels themselves are modest when compared to those from other sources such as road or industrial noise.

Especially the rhythmic character of the sound (technically: Amplitude Modulation or AM) is experienced as annoying and described as a swishing or wooshing sound.

However, recent laboratory studies are inconclusive regarding the effect of amplitude modulation on annoyance. One conclusion is that "there is a strong possibility that amplitude modulation is the main cause of the properties of wind turbine noise". Another dismisses amplitude modulation as a negative factor per se because it is highly related to attitude. A common factor is that AM appears to aggravate existing annoyance, but does not lead to annoyance to persons positive about or benefiting from wind turbines.

The general exposure-effect relation for annoyance from wind turbine sound includes all aspects that influence annoyance and thus averages over all local situations. The relation can therefore give an indication only of the annoyance levels to be expected in a local situation.

Evidence regarding the effect of night time sound exposure on sleep is inconclusive. The current results do not allow a definite conclusion regarding both subjective and objective sleep indicators. However, studies do find a relation between self-reported sleep disturbance and annoyance from wind turbines.

For other health effects there is insufficient evidence for a direct relation with wind turbine sound level.

Based on noise research in general we can conclude that chronic annoyance from wind turbines and the feeling that the quality of the living environment has deteriorated or will do so in the future, can have a negative impact on wellbeing and health in people living in the vicinity of wind turbines. This is similar to the effect of other stressors.

The moderate effect of the *level* of wind turbine sound on annoyance and the range of factors predicting the levels of annoyance implies that reducing the impact of wind turbine sound will profit from considering other factors associated with annoyance. The influence of these factors is not necessarily unique for wind turbines.

6.4 Conclusions from chapter 5

There is substantial knowledge about the physical aspects of low frequency sound. Low frequency sound can be heard daily from road and air traffic and many other sources.

Less is known about infrasound and certainly the perception of infrasound. Infrasound can sometimes be heard, e.g. from big machines and storms, but is not as common as low frequency or 'normal' sound. However, with sensitive equipment infrasound, as well as vibrations, can be measured at large distances.

Infrasound and low frequency sound are present in wind turbine sound. Low frequency sound is included in most studies as part of the normal sound range. In contrast, infrasound is in most studies considered as inaudible as the level of infrasound is low with respect to human sensitivity. Studies of the perception of wind turbine infrasound support this.

Infrasound and low frequency sound from wind turbines have been suggested to pose unique health hazards. There is no scientific evidence to support this. The levels of infrasound involved are comparable to the level of internal body sounds and pressure variations at the ear while walking.

Infrasound from wind turbines is not loud enough to influence the sense of balance (i.e. activate the vestibular system), except perhaps for persons with a specific hearing condition (SCDS).

Effects such as dizziness and nausea, or motion sickness, can be an effect of infrasound, but at much higher levels than wind turbines produce in residential situations.

Vibroacoustic disease (VAD) and the wind turbine syndrome (WTS) are controversial and scientifically not supported. At the present levels of wind turbine sound, the alleged occurrence of VAD or WTS are unproven and unlikely. However, the symptoms associated with WTS are comparable to those found in relation to other stressors.

The rhythmic character of wind turbine sound is caused by a succession of sound pulses produced by the blade rotations. From earlier research it was concluded that this may lead to structural vibrations of a house and wind turbines thus may be perceived indirectly inside a house and hence lead to annoyance. This possibility needs further investigation.

Annex A:

Strategy literature search

For this review a systematic literature search was performed at three moments in time (2000-2012; 2012-2015, 2015-2017). Observational as well as experimental studies described in the peer review literature in the period between 2009 and 2017 was performed. Language was restricted to German, English, French and Dutch. Scopus, Medline and Embase (note: only 2015-2017) were searched. The search strategy is described below.

Only studies which mention in the title, abstract or summary that the association between the noise of wind turbines and reaction, health or wellbeing was studied were included. Also studies addressing participation during the building process were accepted for review. This implied that the association between exposure to wind turbine (low frequency) noise an annoyance, health, wellbeing or activity disturbance in the adult population was studied.

For a first selection the following criteria were used: Inclusion: papers address human health effects, perception, opinion, concern in relation to wind turbines Exclusion: papers address non-human effects such as ecosystem effects, animals, papers about t solely technical aspects of the wind turbines, papers regarding health effects of noise but not specific for wind turbines. This resulted in total in 387 relevant studies.

The papers for the period from January 2015 to February 2017 were grouped in 7 categories: review, health effects, case studies, offshore, low frequency noise, visual aspects, social and not relevant. All reviews and health effects studies were included for full paper examination, offshore studies were a-priori excluded, papers from the other categories were re-considered after reading the abstracts.

Lastly, after full examination of the review and health effect papers by the two authors, a final decision was made about inclusion in this review. As a result 24 new publications were included in the report. Just the week prior to submitting this review the 7th International Wind Turbine Noise Conference was held in Rotterdam. Two relevant papers have been mentioned in this review.

In the context of this report the main results are summarized per outcome. For the key studies, the study design, outcome etc. are discussed in more detail. For this review primarily scientific publications are used, both from peer reviewed journals and conference proceedings. In some cases results are discussed which were described in non-scientific (‘grey’) literature. Also some publications are mentioned which form the base of the debate (discourse) about the risks of living in the vicinity of wind turbines.

As usual all material from the selected literature has been read and analysed, but not necessarily included as reference, e.g. because the study was less relevant than originally thought or in case of doubling with other references. (e.g. a conference paper and article from same authors/study).

Search strategy in Scopus, Medline and (only in last search) Embase databases:

1 (wind turbine* or wind farm* or windmill* or wind park* or wind power or wind energy).ti. (550)

2 turbine noise*.tw. and wind/ (33)

3 (power plants/ or energy-generating sources/ or electric power supplies/) and wind/ (187)

4 (low frequency noise* or low frequency sound* or infrasound or infrasonic noise* or infrasonic sounds or infrasonic frequencies or low frequency threshold or (noise* adj4 low frequenc*)).ti. (500)

5 1 or 2 or 3 or 4 (1113)

6 (wind turbine* or wind farm* or windmill* or wind park* or wind power or wind energy).ab. (803)

7 (low frequency noise* or low frequency sound* or infrasound or infrasonic noise* or infrasonic sounds or infrasonic frequencies or low frequency threshold or (noise* adj4 low frequenc*)).ab. (1487)

8 noise*.ti. (26930)

9 (6 or 7) and 8 (498)

10 (impact or perception* or perceive* or health* or well-being or "quality of life" or syndrome*).ti. (1456358)

11 (annoyance or annoying or annoyed or aversion or stress or complaints or distress or disturbance or adversely affected or concerns or worries or noise problems or noise perception or

noise reception or noise sensitivity or (sensitivity adj3 noise) or sound pressure level* or sleep disturbance* or sleep quality or cognitive performance or emotions or anxiet* or attitude*).tw. (1260490)

12 (social barrier* or social acceptance or popular opinion* or public resistance or (living adj4 vicinity) or (living adj4 proximity) or (residing adj4 vicinity) or (residing adj4 proximity) or living close or "living near" or residents or neighbors or neighbours).tw. (105942)

13 (soundscape or landscape or visual annoyance or visual interference or visual perception or visual impact or visual preferences or visual assessment or visual effects or perceptual attribute*).tw. (41227)

14 ((effects adj4 population) or dose-response relationship* or exposure-response relationship* or dose response or exposure response or human response or health effects or health aspects or health outcome*).tw. (136924)

15 (flicker or reflection).ti. (10980)

16 environmental exposure/ or noise/ae or environmental pollution/ae (79725)

17 loudness perception/ or psychoacoustics/ or auditory perception/ or auditory threshold/ or sensory thresholds/ or visual perception/ or motion perception/ (130572)

18 sleep disorders/ or emotions/ or anger/ or anxienty/ or quality of life/ or epilepsy/ or attitude/ or affect/ or pressure/ or esthetics/ or social environment/ or risk factors/ (1232239)

19 (physiopathology or adverse effects).fs. (3235762)

20 (5 or 9) and (10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19) (600)

21 20 and (english or dutch or french or german).lg. (509)

22 21 not (animals/ not humans/) (369)

23 limit 22 to yr=2014-2017 (129)

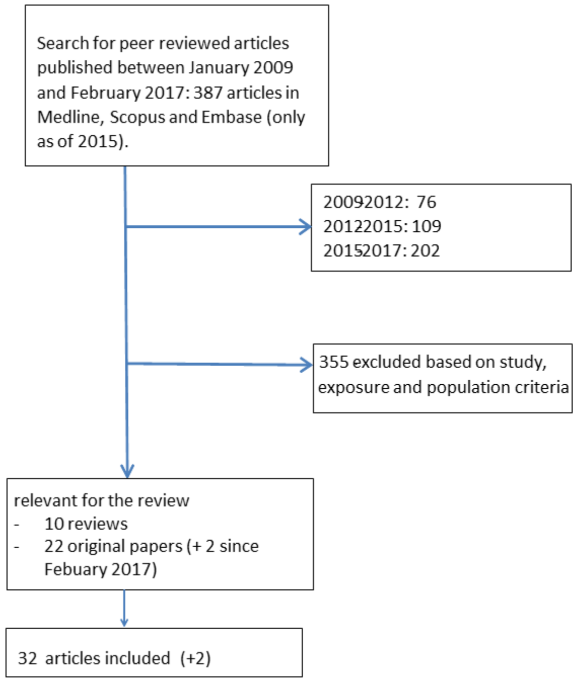
24 limit 23 to ed=20150122-20161228 (81)

25 limit 23 to yr=2015-2017 (90)

26 24 or 25 (110)

27 remove duplicates from 26 (96)

As the diagram below shows, the literature searches yielded 387 publications of which 107 were relevant for the review and in the end 32 (+2) are included in the reference list (annex B).



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