EXHIBIT A5

BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE APPLICATION BY PREVAILING WIND PARK, LLC FOR A PERMIT FOR A WIND ENERGY FACILITY IN BON HOMME, CHARLES MIX, AND HUTCHINSON COUNTIES, SOUTH DAKOTA, FOR PREVAILING WIND PARK ENERGY FACILITY

SD PUC DOCKET EL-18-026

PREFILED REBUTTAL TESTIMONY OF DR. MARK ROBERTS
ON BEHALF OF PREVAILING WIND PARK, LLC

September 26, 2018

I. INTRODUCTION

Q. Please state your name.

A. My name is Dr. Mark Roberts.

Q. Did you provide Supplemental Direct Testimony in this Docket?

A. Yes. I submitted Supplemental Direct Testimony in this docket on August 10, 2018.

Q. What is the purpose of your Rebuttal Testimony?

A. The purpose of my Rebuttal Testimony is to respond to the testimony of Professor Mariana Alves-Pereira, Jerry Punch, Ph.D., and Richard James, each of whom submitted testimony on behalf of Intervenors in this docket.

Q. Are there any exhibits attached to your Rebuttal Testimony?

A. The following exhibits are attached to my Rebuttal Testimony:

- Exhibit 1: Ministry for the Environment, Climate and Energy of the Federal State of Baden-Wuerttemberg, Germany (2016). *Low-frequency Noise Incl. Infrasound from Wind Turbines and Other Sources*. LUBW Landesanstalt fur Umwelt, Messungen and Naturschutz Baden-Wuerttemberg.
- Exhibit 2: Akira Shimada and Mimi Nameki (2017). *Evaluation of Wind Turbine Noise in Japan. Ministry of the Environment of Japan.*
- Exhibit 3: Danish Energy Agency (2009). *Wind Turbines in Denmark.*
- Exhibit 4: Frits van den Berg, Public Health Service Amsterdam, and Irene van Kamp, National Institute for Public Health and the Environment (2017). *Health effects related to wind turbine sound. Swiss Federal Office for the Environment.*
- Exhibit 5: Stephen Chiles (2010). *A new wind farm noise standard for New Zealand, NZS 6808:2010*. Proceedings of 20th International Congress on Acoustics, ICA 2010.

- Exhibit 6: Eja Pedersen, Högskolan i Halmstad (2003). *Noise Annoyance 116 from Wind Turbines: A Review.* Swedish Environmental Protection Agency.

- Exhibit 7: Hitomi Kimura, Yoshinori Momose, Hiroya Deguchi, and Nameki, Mimi (2016). *Investigation, Prediction, and Evaluation of Wind Turbine Noise in Japan.* Ministry of the Environment of Japan.

- Exhibit 8: C. Yan, K. Fu and W. Xu. *On Cuba, diplomats, ultrasound, and intermodulation distortion. University of Michigan Tech Report*. March 1, 2018.

- Exhibit 9: Crichton, F., et al. (2014). *The link between health complaints and wind turbines: Support for the nocebo expectations hypothesis*. *Frontiers in Public Health* 2:220.

- Exhibit 10: Enck, P., et al. "New Insights Into the Placebo and Nocebo Responses," Neuron (July 31, 2008): Vol. 59, No. 2, pp. 195–206.

- Exhibit 11: Colloca, L. (2017). *Nocebo effects can make you feel pain: Negative expectancies derived from features of commercial drugs elicit nocebo effects*. *Science*, 358(6359): 44.

II. RESPONSE TO TESTIMONY OF PROFESSOR MARIANA ALVES-PEREIRA

A. Overview.

Q. Have you reviewed the Prefiled Testimony of Prof. Mariana Alves-Pereira, submitted on behalf of Intervenors in this proceeding?

A. Yes. I reviewed Prof. Alves-Pereira's testimony, as well as the exhibits attached to her testimony.

Q. Please summarize your response to Prof. Alves-Pereira's testimony.

A. As I discussed in my Supplemental Direct Testimony, I am aware of Prof. Alves-Pereira's assertions regarding vibroacoustic disease. A majority of the work involving vibroacoustic disease has originated from Dr. Castelo Bronca's research group in Portugal, of which Prof. Alves-Pereira is a member. A majority of the research group's efforts have focused on low frequency sound at high levels (*e.g.*, 120 decibels and above, well above the sound levels of wind turbines). Their work has not been replicated by other research groups to the point where vibroacoustic disease has been accepted as a medical diagnosis. As I discussed previously, based on my work and review of reliable scientific literature, I am not aware of any link between wind turbines and what Prof. Alves-Pereira describes as vibroacoustic disease.

B. <u>Scientific Method</u>.

Q. Professor Alves-Pereira references the scientific method and evidence-based medicine in her testimony. (Alves-Pereira Direct, lines 63-66.) Please describe these concepts.

A. I previously discussed the scientific method in detail in my Supplemental Direct Testimony. To summarize, during a clinical encounter between a patient and a physician, medical information is collected and analyzed. First, the physician will note the patient's report of symptoms and concerns. That consists of what the patient says he or she is experiencing. This may include the patient's attribution of their symptoms (headache, dizziness, upset stomach, etc.) to some event or activity. This is often referred to as the "subjective" information and refers to what the patient reports. Next, the physician attempts to obtain information that will verify or clarify the patient's reported symptoms or concern (objective information). This verification consists of probing questions to clarify the information and includes assessment of past medical history (previous injury or illness), collection of information during the physical examination, and testing (laboratory and or imaging). Next, the physician assesses the subjective information and the objective evidence and compares this information with the physician's clinical experience, training, and other medical knowledge to arrive at a diagnosis and a plan for treatment. In common conditions (flu, high blood pressure, gastrointestinal conditions, etc.), the physician will usually have sufficient experience to make the diagnosis without going into the published literature. In other cases, the physician may need to gather additional information or refer the patient on to a specialist.

For an example of this process: Patient comes to the doctor with severe headache and is concerned that he might have a brain tumor. The doctor does not immediately schedule the patient for brain surgery but instead evaluates the patient in an orderly process that rules in or rules out the presence of a brain tumor. The physician evaluates what the patient reports, the outcome of the physical examination and tests or imaging, then assesses this information, makes a diagnosis, and develops a treatment plan.

Q. Prof. Alves-Pereira asserts that "[w]hen it comes to studying the health effects of ILFN exposure, however, these fundamental axioms of the Scientific Method and Evidence-based Medicine are somehow forgotten, or deemed not applicable." (Alves-Pereira Direct, lines 68-70.) What is your response?

A. I do not agree. The publications attached to my Supplemental Direct Testimony and this Rebuttal Testimony utilize the scientific method. Despite Prof. Alves-Pereira's assertions otherwise, it is not sufficient to take the patient's reported health concerns and immediately draw a conclusion regarding causation without including an evaluation of objective evidence and appropriate peer-reviewed, published literature. The key point is to look at the "evidence" – that is, objective findings from a clinical evaluation conducted by a physician that bases opinions based on data that has passed review.

Q. Prof. Alves-Pereira states that "[a]nnoyance is not an objective parameter and hence, in accordance with the axioms of Evidence-based Medicine, cannot be

used to ascertain de facto health effects." (Alves-Pereira Direct, lines 77-78.) What is your response?

A. I agree. This statement is consistent with my prior testimony and the fact that "annoyance" is the most commonly recognized "effect" in the applicable peer-reviewed published literature and the reviews by scientific committees that I have previously identified. Annoyance in and of itself is not a health effect but instead is a normal physiological response to one's surroundings. As I have testified many times before, one person's music can be perceived as an annoying noise by another person. It is the perception of the noise that often makes it annoying - not the noise itself. I note, however, that Prof. Alves-Pereira's statement here seems inconsistent with the remainder of her testimony. She appears to transform complaints of annoyance into objective health issues solely because the complaints were described to a doctor.

Q. Prof. Alves-Pereira states that, "[i]n accordance with the axioms of Evidence-based Medicine and, even more fundamentally, the Scientific Method, *psychosomatic illnesses must also be clinically corroborated*; their proposed existence based on mere assertions is not scientifically valid." (Alves-Pereira Direct, lines 83-86.) What is your response?

A. Again, I agree. This statement is entirely consistent with my testimony and well-accepted peer-reviewed literature. However, it is not consistent with the remainder of Prof. Alves-Pereira's testimony, where she indicates that a person's report of illness is sufficient for there to be the documented occurrence of a health issue related to wind turbines.

Q. Prof. Alves-Pereira discusses the scientific validity of self-reported health complaints in lines 134-50 of her testimony. Do you have a response?

A. Yes. Prof. Alves-Pereira's discussion is not consistent with the normal clinical process I have previously described in this testimony. Self-reported health complaints are certainly part of the clinical process, but they do not become scientifically valid simply because they are reported to a physician. Rather, as I discussed previously, a patient's self-reported health complaints are subjective information – they are one part of the clinical evaluation process, but a patient's recitation of a series of subjective symptoms to a physician does not make those symptoms objective evidence. Prof. Alves-Pereira uses the term *anamnesis* to bolster her argument. Although a medical term, the term *anamnesis* simply refers to the patient history as described by the patient. It does not confer special verification. Again, in the normal clinical process, the physician takes what the patient reports, what is identified from the physical examination along with any laboratory testing or imaging results, and compares this information to his or her clinical experience, training, and current medical information to make a diagnosis, if possible, and set out a treatment plan, or refers the patient on to a specialist for further assessment.

C. <u>Infrasound and Wind Turbines</u>.

Q. Prof. Alves-Pereira discusses infrasound and low-frequency noise, or "IFLN." What is infrasound?

A. As I described in my Supplemental Direct Testimony, infrasound is sometimes referred to a[illegible]ound and is sound that is between 0 hertz ("Hz") and 20 Hz. A level of 20 Hz is commonly considered to be the low end of the range of human hearing. It is very important to specify the sound because the human ear responds differently to different frequencies.

Q. What are sources of infrasound?

A. As I noted in my Supplemental Direct Testimony, human organs produce infrasound. For example, heart sounds are in the range of 27 to 35 dBA at 20-40 Hz, and lung sounds are reported in the range of 5-35 dBA at 150-600 Hz; these sources are in the range of sound produced by wind turbines. In addition, infrasound comes from numerous natural and man-made sources. With respect to natural sources, waves, thunder, and waterfalls are natural sources of infrasound. With respect to man-made sources, common household objects such as washing machines, fans and heating and refrigeration systems are also sources of infrasound.

Q. Professor Alves-Pereira discusses infrasound, particularly that from wind turbines, and its potential impacts on human health. Are you aware of any recent studies on this topic?

A. Yes. Researchers in the United States (Massachusetts) (2012) (Roberts Supplemental Direct Testimony, Exhibit 7), Germany (2016) (Exhibit 1), Japan (2017) (Exhibit 2), France (2017) (Roberts Supplemental Direct Testimony, Exhibit 3), Denmark (2009) (Exhibit 3), Switzerland (2017) (Exhibit 4), New Zealand (2010) (Exhibit 5), Sweden (2003) (Exhibit 6), and Australia (2015) (Roberts Supplemental Direct Testimony, Exhibit 2c) have reviewed the literature regarding infrasound from wind turbines. Each study, using recognized scientific methods, concluded that infrasound levels are multiple orders of magnitude below the threshold of human hearing. For example, the 2016 German study concluded that "[t]he infrasound levels generated by [wind turbines] lie clearly below the limits of human perception. There is no scientifically proven evidence of adverse effects in this level range." (Exhibit 1, at 12.) Similarly, the Ministry of the Environment of Japan's 2016 study *Investigation, Prediction, and Evaluation of Wind Turbine Noise in Japan* states that, "Super-low (below 20 Hz) frequency range components of wind turbine noise are at imperceptible levels. Therefore, wind turbine noise is not an issue caused by super-low frequency range." (Exhibit 7, at 5760.) These are just a few of the reports of expert panels at state, national, and international levels that have not found a specific health condition associated with wind turbines.

An independent review of the literature relative to wind turbines and health was commissioned by the National Health and Medical Research Council ("NHMRC") with the goal of determining whether there was an association between exposure to wind farms and human health effects. The document is approximately 300 pages and covers peer-reviewed, published literature, government reports, and some lay publications. The overall conclusions of this extensive review were:

> "[t]here is no consistent evidence that noise from wind turbines—whether estimated in models or using distance as a proxy—is associated with self-reported human health effects. Isolated associations may be due to confounding, bias or chance." (Roberts Supplemental Direct Testimony, Exhibit 2c.)

Most recently, the March 2017 French National Agency for Food Safety, Environment and Labor ("ANSES") carried out measurement campaigns near three wind farms. A summary of this study is included as Exhibit 3 of my Supplemental Direct Testimony (the original study is in French). The summary notes that the study concluded:

- "the results of these campaigns confirm that wind turbines are sources of infrasound and low sound frequencies, but no exceedance of the audibility thresholds in the areas of infrasound and low frequencies up to 50 Hz has been found";[1] and
- "all the experimental and epidemiological data available today do not show any health effects related to exposure to noise from wind turbines, other than noise-related annoyance."

(Roberts Supplemental Direct Testimony, Exhibit 3.)

Q. Do you agree with the ANSES conclusions?

A. Yes. They are consistent with the peer-reviewed literature on wind turbine noise.

Q. In response to the question, "[w]hy are some people affected and others not within the same household" regarding infrasound, Prof. Alves-Pereira

[1] French Agency for Food, Environmental and Occupational Health & Safety, *Exposure to low-frequency sound and infrasounds from wind farms: improving information for local residents and monitoring noise exposure* (Mar. 30, 2017), https://www.anses.fr/en/content/exposure-low-frequency-sound-and-infrasounds-wind-farms-improving-information-local; *see also* Roberts Supplemental Direct Testimony, Exhibit 3.

discusses "two exposure-linked factors." (Alves-Pereira Direct, lines 180-88.) Do you have a response?

A. Yes. First, without evidence, Prof. Alves-Pereira asserts that individuals are negatively affected by infrasound. Second, Prof. Alves-Pereira makes the assertion that two "exposure-linked factors" "profoundly condition the onset of symptoms among families living in ILFN-contaminated homes." She identifies these factors as "prior ILFN exposure histories" and "residential time exposure patterns." Although these phrases may sound official and technical, they are not. Prof. Alves-Pereira provides no scientific support for her assertions, and I am not aware of any. We are all exposed to all sorts of sounds all the time. None of the reviews by governmental organizations and other groups of scientists impaneled to review the material relative to wind turbine sound and health effects have referenced the process of "exposure-linked processes" that Prof. Alves-Pereira has used.

Q. In response to the same question, Prof. Alves-Pereira then discusses "individual susceptibility factors." (Alves-Pereira Direct, line 189.) Do you agree?

A. No. As with her assertions regarding "exposure-linked factors," Prof. Alves-Pereira provides no scientific support for her statements, and I am not aware of any.

Q. Prof. Alves-Pereira states that she and her group are collecting data regarding wind turbines, including "conducting extensive interviews among the complaining populations." (Alves-Pereira Direct, line 214.) What are your thoughts on these statements?

A. Prof. Alves-Pereira's statements demonstrate the serious flaws of her described "study." It is hard to evaluate the study without reading it, but Prof. Alves-Pereira's reliance on "complaining populations" without comparison to noise exposure measurements and her evaluation of common everyday health issues has been repeated by many researchers opposed to wind energy, starting with Prof. Nina Pierpont. This method of research is fraught with bias that cannot be overcome. Prof. Alves-Pereira appears to have already concluded that her research is going to find adverse health impacts from wind turbines. As such, she is only conducting interviews with complaining persons. However, the research she describes collects, at best, anecdotal information. As I have stated time and again, interviewing complaining populations is not an epidemiological study and does not follow the scientific method that must be followed to move from an observation, to correlation, and ultimately to causal proof.

Q. Prof. Alves-Pereira asserts that "[s]afe distances have not yet been established for the IFLN generated by wind turbines." Do you agree with this conclusion?

A. No. Again, Prof. Alves-Pereira implies that there are adverse health effects from wind turbines, but she fails to back up these claims with scientific data. Put simply, adverse health effects have not been linked to infrasound generally or to infrasound generated by wind turbines, more specifically.

D. <u>Prof. Alves-Pereira's Statements Regarding My Supplemental Direct Testimony</u>.

Q. Prof. Alves-Pereira asserts that your testimony treats wind turbines, rather than infrasound, as "agents of disease." Do you agree?

A. No. Prof. Alves-Pereira misunderstands my testimony and my opinions. What I have clearly stated is that the peer-reviewed, published literature and the results of numerous reviews of that literature do not indicate that infrasound at the levels generated by a wind turbine is an "agent of disease." I certainly have not confused these concepts, as Prof. Alves-Pereira appears to believe. However, the literature also clearly identifies the presence of wind turbines as a point of annoyance for some individuals.

Q. Prof. Alves-Pereira asserts that "studies comparing people who live near wind turbines with those who do not" are not scientifically valid. (Alves-Pereira Direct, lines 314-15.) Do you agree?

A. No, not at all. The cornerstone of an epidemiological study – and the scientific method – is the fact that there is a comparison group. It is critical to have a comparison group to determine whether there is an increase in health factors – This is especially important with respect to issues like wind turbine effects, where there are subjective complaints with the overlay of annoyance.

Q. Professor Alves-Pereira asserts that "receiving 10 chest x-rays per day for a year, might indeed begin to pose a problem in terms of health effects. It is the same with IFLN." (Alves-Pereira Direct, lines 363-64.) Do you agree?

A. This is not a valid comparison. There is a significant body of reliable, published, peer-reviewed literature regarding the adverse effects of x-rays, starting with Madame Curie. By contrast, there is <u>no</u> evidence that the sound levels generated by wind turbines cause specific health effects, let alone any health effects separate and distinct from the infrasound we are exposed to in our environment 24 hours a day.

E. <u>Discussion of Certain Exhibits to Professor Alves-Pereira's Testimony</u>.

Q. Prof. Alves-Pereira attaches a document titled *Neurological Manifestations Among US Government Personnel Reporting Directional Audible and Sensory Phenomena in Havana, Cuba* as Exhibit 3 to her testimony ("Havana Paper"). Are you familiar with the Havana Paper?

A. Yes. The "Havana Paper" is a brief description of health investigations of U.S. government personnel serving on diplomatic assignment in Havana, Cuba, that they experienced "neurological symptoms" thought to be associated with exposure to auditory and sensory phenomena in 2016 and 2017.

Q. In your opinion, does the Havana Paper provide the Commission with helpful information related to this Project?

A. No. Prof. Alves-Pereira asserts that the symptoms reported by the Cuban diplomats "are very similar to those made by families living in ILFN-contaminated homes."

This assertion is not well-founded. Diplomatic staff complained of a high-pitched noise. Researchers at the University of Michigan analyzed audio records provided by the United States Department of State. The researchers' analysis indicated that the sound recording in the Cuba Embassy was a mixture of high frequency sound (ultrasound) in the thousands of Hz range. The sound identified as potentially affecting Cuban diplomats was thousands of times higher than the frequencies generated by wind turbines. (Yan, et al. 2018, Exhibit 8.) Prof. Alves-Pereira's comparison of the Cuban Embassy investigation is misguided and inapt.

Q. Prof. Alves-Pereira attaches a document titled *Occupational and Residential Exposures to Infrasound and Low Frequency Noise in Aerospace Professionals: Flawed Assumptions, Inappropriate Quantification of Acoustic Environments, and the Inability to Determine Dose-Response Values* as Exhibit 4 to her testimony ("Aerospace Paper"). Are you familiar with the Aerospace Paper?

A. Yes. The Aerospace Paper is co-authored by Prof. Alves-Pereira and asserts, as Prof. Alves-Pereira does in her testimony, that the dBA metric is not adequate to protect against excessive infrasound exposure.

Q. In your opinion, does the Aerospace Paper provide the Commission with helpful information related to this Project?

A. No. This paper focuses on the noise levels associated with the aerospace industry, which are orders of magnitude greater that the noise levels measured at wind farms. The graphs shown in that paper are illustrating levels of 70+ decibels. In addition, under the disclaimer on page 96 of the paper, the authors state that they "[a]re not producing an environmental noise assessment report focused on wind turbines."

Q. Prof. Alves-Pereira attaches a document titled *Infrasound and Low Frequency Noise: Shall we Measure it Properly?* as Exhibit 5 to her testimony ("ILFN Paper"). Are you familiar with the ILFN Paper?

A. Yes. As Prof. Alves-Pereira notes, it is a "more informal paper" that described her fieldwork in Ireland.

Q. In your opinion, does the ILFN Paper provide the Commission with helpful information related to this Project?

A. No. The paper lacks significant information needed to assess it. First, the testing does not report background levels of low frequency sound in the homes. Secondly, there is no indication of the type of wind turbine or power output that could give the reader an indication of the contribution of these factors. The report uses a set of observations that are not adequately described to bolster Prof. Alves-Pereira's claims regarding low frequency noise measurements. In addition, the report does not appear to have been published, which would have subjected it to peer review.

Q. Prof. Alves-Pereira attaches a document titled *An Evaluation of Environmental, Biological, and Health Data from the Island of Vieques, Puerto Rico* as Exhibit 6 to her testimony ("Vieques Paper"). Are you familiar with the Vieques Paper?

A. Yes.

Q. In your opinion, does the Vieques Paper provide the Commission with helpful information related to this Project?

A. No. The Vieques Paper highlights how the investigation of public health events can be performed but sheds no light on the questions regarding wind turbines and health. It does, however, highlight the fact that the claim made by the Portuguese reseach group that there was a high level of vibroacoustic disease among Vieques fisherman was not confirmed by an independent review panel. Rather, the independent review panel determined, after conducting blind-coding and repetition of that analysis by Mayo Clinic, that there was no evidence to indicate clinically significant heart disease. (Alves-Pereira Direct, Exhibit 6 at A-52.)

Q. Prof. Alves-Pereira attaches a document titled *Vibroacoustic Disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signalling* as Exhibit 7 to her testimony ("2006 VAD Paper"). Are you familiar with the 2006 VAD Paper?

A. Yes.

Q. In your opinion, does the 2006 VAD Paper provide the Commission with helpful information related to this Project?

A. No. As noted by the researchers in the 2006 VAD Paper, there has been "much controversy and acrimonious debate over whether or not acoustical phenomena can cause extra-auditory effects on living organisms." In addition, it is not evident from a review of the published literature that the findings, referred to as vibroacoustic disease or "VAD" by these researchers, has been confirmed by others or generally accepted by medical or acoustical professions. There are no epidemiologically-sound studies that have found what these researchers refer to as vibroacoustic disease associated with wind turbines. The fact that there is not widespread acceptance is evidenced by the fact that the International Classification of Disease 10th Edition ("ICD-10") does not list vibroacoustic disease. The ICD-10 is the tenth revision of the codes for recognized diseases, health complaints, and causes for disease and injury listed by the World Health Organization and is used by the National Center for Health Statistics to code and classify illness and deaths in the United States. The ICD-10 classification lists over 14,000 major diseases and injuries but can be expanded to 70,000 codes when the major categories are expanded.

Q. Prof. Alves-Pereira attaches a document titled *Vibroacoustic Disease I: The Personal Experience of a Motorman* as Exhibit 8 to her testimony ("Motorman Paper"). Are you familiar with the Motorman Article?

A. Yes. This is a layperson's account of a presumed occupational exposure to low-frequency sound.

Q. In your opinion, does the Motorman Article provide the Commission with helpful information related to this Project?

A. No. The Motorman Article is a layperson's opinion and has no scientific data to contribute to a discussion about wind turbines.

Q. Prof. Alves-Pereira attaches a document titled *Vibroacoustic Disease and Respiratory Pathology III – Tracheal and Bronchial Lesions* as Exhibit 9 to her testimony ("VAD Respiratory Paper"). Are you familiar with the VAD Respiratory Paper?

A. Yes. This is a case series published by Prof. Alves-Pereira's research group. It is a report of the results of biopsies of the respiratory tract of four individuals (two of whom were smokers), three of whom were employed in occupations involving aviation, and all of whom had been diagnosed with what Prof. Alves-Pereira terms vibroacoustic disease. As pointed out earlier, case series are not epidemiological studies.

Q. In your opinion, does the VAD Respiratory Paper provide the Commission with helpful information related to this Project?

A. No. This paper has nothing to do with wind turbines. It also does not follow the scientific method of risk evaluation – there is no objective assessment of intensity, duration, or frequency of low-frequency noise exposure that would identify whether any of the individuals experienced low-frequency noise above normal background levels. In addition, there is no assessment of the individuals' occupational history, which could have included chemical exposures that adversely affect the upper respiratory system and potentially produce cell damage similar to that described in the case series.

Q. Prof. Alves-Pereira attaches a document titled *Vibroacoustic Disease in a Ten Year Old Male* as Exhibit 10 to her testimony ("2004 VAD Paper"). Are you familiar with the 2004 VAD Paper?

A. Yes.

Q. In your opinion, does the 2004 VAD Paper provide the Commission with helpful information related to this Project?

A. No. This is a case report of claimed low-frequency noise exposure, but it is not clear that the source was identified, nor was the sound level quantified sufficiently to support the claimed effect. Once again, a "diagnosis" of what Prof. Alves-Pereira describes as vibroacoustic disease is made when, in fact, this is not a clinically recognized medical condition beyond the Portuguese researchers.

F. <u>Conclusion Regarding Prof. Alves-Pereira's Testimony</u>.

Q. What is your overall impression of Prof. Alves-Pereira's Testimony?

A. Prof. Alves-Pereira has not established that the peer-reviewed, published literature has documented a health problem associated with low-frequency sound at the levels generated by wind turbines, let alone that low-frequency sound from any source causes such health problems.

III. RESPONSE TO TESTIMONY OF JERRY PUNCH, Ph.D.

Q. Have you reviewed the Prefiled Testimony of Jerry L. Punch submitted on behalf of Intervenors in this matter?

A. Yes. I reviewed the testimony submitted by Dr. Punch, as well as the exhibits attached to that testimony.

A. <u>2016 Punch and James Paper</u>.

Q. On page 4 of his testimony, Dr. Punch references an article he authored titled *Wind turbine noise and human health: a four-decade history of evidence that wind turbines pose risks*, which he attaches as Exhibit 2 to his testimony (the "2016 Punch and James Paper"). Are you familiar with the 2016 Punch and James Paper?

A. Yes. I have observed this article on a number of anti-wind websites and seen it produced at various hearings. It is not consistent with the opinions of local, state, national, and international panels of experts who have reviewed the peer-reviewed, scientific publications related to wind turbines and health effects.

Q. Dr. Punch states that the 2016 Punch and James Paper was peer reviewed. Do you agree?

A. No. A summary of the 2016 Punch and James Paper describes the purported "peer review" of this paper as follows:

> This paper has been reviewed both by the anonymous Noise & Health reviewer and by three other reviewers who have substantial professional experience in the area of wind turbine noise. We gratefully acknowledge the helpful contributions of Keith Johnson, Esq., Michael Nissenbaum, MD, and Daniel Shepherd, PhD.
>
> Mr. Johnson provided a review from the perspective of an attorney who represents interveners in wind turbine siting cases. Dr. Nissenbaum provided a review from the perspective of a medical professional and expert in how ionizing and non-ionizing radiation affects humans. Dr. Shepherd provided a review from the perspective of a psychoacoustician with experience in how wind turbine sound affects people. Each of these reviewers' comments on earlier versions of our manuscript led to the final document. The opinions or assertions contained herein, however, are the personal views of the authors and are not to be

construed as reflecting the views of Michigan State University or Central Michigan University.[2]

This does not describe the typical level of rigorous peer review I would expect before labeling a report "peer reviewed." A law degree is not recognized as a science degree and, notably, Mr. Johnson is described as representing opponents to wind projects. It is also notable that Dr. Nissenbaum is on the Board of Directors of "The Society for Wind Vigilance," which is a well-known and decidedly anti-wind group.[3] Similarly, Dr. Shepherd is one of that group's "Scientific Advisors."[4] As such, these "reviewers" may have been predisposed to agreeing with Dr. Punch and with groups opposed to wind energy.

Q. In your opinion, does the 2016 Punch and James Paper provide the Commission with helpful information with respect to this Project?

A. No. The stated goal of the article is to "provide a systematic review of legitimate sources that bear directly and indirectly on the question of the extent to which WT noise leads to the many health complaints that are being attributed to it." The authors state that they used Google, Google Scholar, and PubMed for this information. I note that a Google search regarding wind turbines and health effects returns millions of results, which are not consistently reviewed or otherwise fact-checked. The scientific alternative is the U.S. National Library of Medicine, National Institute of Medicine's PubMed, which comprises more than 28 million citations for biomedical literature from MEDLINE, life science journals, and online books. My PubMed search of "wind turbines health effects" on September 23, 2018, returned only 54 articles in the scientific literature. In my experience, there is a lot of

[2] *See National Wind Watch: Presenting the Facts about Industrial Wind Power* website link, *available at* https://www.wind-watch.org/documents/wind-turbine-noise-and-human-health-a-four-decade-history-of-evidence-that-wind-turbines-pose-risks/ (last accessed Sept. 19, 2018).

[3] Dr. Punch's co-author, Richard James, is also on this Board of Directors. Similarly, Drs. Phillips, Salt, and Thorne, each of whom are quoted in the 2016 Punch and James Paper, are "Scientific Advisors" to The Society of Wind Vigilance and have each written opinion pieces against wind turbines.

[4] *See* http://www.windvigilance.com/home/advisory-group (last accessed Sept. 19, 2018).

"information" in the lay press, internet, or word of mouth, but very little of it is objective scientific evidence.

Q. Dr. Punch states: "I believe that a substantial proportion of people living in the vicinity of the proposed Project can be expected to experience not only annoyance, but also a variety of adverse health effects." Do you agree?

A. No. Dr. Punch's "belief" is not a scientifically-validated conclusion. His "belief" is also not supported by the published, peer-reviewed literature on this topic, as I discussed in my Supplemental Direct Testimony. Annoyance is not a health effect but a normal, everyday psychological and physiological response often manifested when a person does not like or does not agree with something occurring in his or her life. For example, a baby crying may be reassuring to a mother that the baby is breathing, is hungry, or needs its diaper changed, but a crying baby on an airplane may be annoying to some fellow passengers.

Q. Dr. Punch asserts that the 2016 Punch and James Paper "indicate[s] that there is a strong association between exposure to wind turbines and the health complaints, and they strongly suggest that the link is causative." (Punch Direct, lines 150-52.) Do you agree?

A. No. Based on Dr. Punch's testimony, he is not relying upon evidence from epidemiological studies conducted using the scientific method. To the extent Dr. Punch is referring to the process of asking individuals if they experienced health conditions before wind turbines were installed, this is not a reliable study method, as I have previously discussed (*e.g.*, recall bias).

Q. Dr. Punch states that "general causation and specific causation . . . differ based on the targets of interest: the general population versus targeted individuals, respectively." (Punch Direct, lines 159-60.) Do you agree with this characterization?

A. No, Dr. Punch is not correct. General causation refers to the science that identifies the cause of disease - the risk factors or characteristics generally associated with the development of a disease. Specific causation refers to the determination that an individual has the risk factors or characteristics associated with the disease or health condition at a sufficient level to reasonably conclude the cause of an individual's disease or health condition.

B. <u>Dr. Punch's Statements Regarding My Supplemental Direct Testimony</u>.

Q. Dr. Punch states that your "testimony rests primarily on [your] credentials in epidemiology and apparently not on [your] first-hand experience with people who have been exposed to wind turbine noise over long periods of time." (Punch Direct, lines 175-77.) Do you have a response?

A. Dr. Punch appears to misunderstand what qualifies someone to evaluate an exposure situation based on the scientific method. I spent 17 years in the Oklahoma State Department of Health. During most of that time, I evaluated health concerns involving communicable and environmentally-related disease for Oklahoma residents. I use the same scientific method to evaluate health concerns anytime I am asked to evaluate a potential exposure situation, regardless of the purported cause.

Q. Dr. Punch also states that you "essentially dismiss[ ] most of the nine [Bradford Hill] criteria by naming them, without discussing their implications." (Punch Direct, lines 180-81.) What are the Bradford Hill criteria?

A. The "Bradford Hill" criteria were proposed by Sir Austin Bradford Hill in 1965. They are a set of nine criteria to provide epidemiologic evidence of a causal relationship between a presumed cause and an observed effect when the association of cause and effect are sufficiently identified. In other words, the criteria are used to evaluate the strength of an association between a disease and its supposed causative agent. Sir Bradford Hill made it clear in his 1965 Presidential Address at the Royal Society of Medicine where he stated *"Disregarding then any such problem in semantics we have this situation. Our observations reveal an association between two variables,* *perfectly clear-cut and beyond what we would care to attribute to the play of chance. What aspect of that association should we especially consider before deciding that the most likely interpretation of it is causation?"* Sir Bradford Hill then went on to list his nine criteria.

Q. What is your response to Dr. Punch's assertion that you "dismissed" the Bradford Hill criteria?

A. I disagree. My assessment methods are consistent with the Bradford Hill criteria. It is apparent from the peer-reviewed, published research that specific health effects have not been proven to be associated with sounds produced by wind turbines.

Q. Dr. Punch cites a paper prepared by Dr. Carl Phillips. Are you familiar with Dr. Phillips?

A. Yes. Despite Dr. Punch's statement otherwise, Dr. Phillips is not an epidemiologist. Instead, he holds a Ph.D. in public policy and is a "Scientific Advisor" to the Society for Wind Vigilance.[5] As I noted earlier, this is a well-known anti-wind group.

Dr. Phillips' arguments center on the opinion that there is sufficient "scientific evidence" that wind turbines cause a multitude of symptoms and disease for residents living nearby. The basis of his opinion is that "people can observe that the noise from the turbines seems to be bothering them, and can surmise that what they are noticing may be causing their disease." While this sort of information provides impetus to explore what might be the underlying health issues and concerns, it does not confirm a causal pathway. It is, at most, an association that requires careful evaluation and hypothesis testing. An observation of noise that one concludes is bothersome does not necessarily translate into a cause of disease without objective measurements. As I have discussed previously, others who have done these kinds of objective measurements have, in fact, *not* found any causal relationship between wind turbines and adverse health effects.

[5] *See* http://www.windvigilance.com/home/advisory-group/bio_phillips, *last accessed* Sept. 19, 2018.

C. <u>The Nocebo Effect</u>.

Q. Dr. Punch attempts to critique your discussion of the "nocebo effect." What is the nocebo effect?

A. The nocebo effect is the recognized human response to a negative belief or impression. For example, if a patient does not think that a medication will be effective, there is a high probability that the medication will not be effective. Nocebo is the opposite of placebo, which is the normal response observed where, when a person thinks a medication will be effective, it is more likely to be effective. The nocebo effect has been described as follows: "When individuals expect a feature of their environment or medical treatment to produce illness or symptoms, then this may start a process where the individual looks for symptoms or signs of illness to confirm these negative expectations." (Crichton, et al. 2014, Exhibit 9.)

Q. What is the relevance of the nocebo effect to this proceeding?

A. There is clear evidence in the medical literature regarding both the placebo effect and nocebo effect. (Meissner 2011.) It is real, and it is key to understanding health complaints about phenomena that occur around us. Research going back decades indicates that one's perception dictates the physical and emotional response. The development of social media and the internet has only intensified this focus. Research into recent events such as the Boston Marathon bombing and Sandy Hook shootings have shown that media coverage has broadened the extent of the psychological effect. (Holman 2014.) One has to look no farther than the internet to find a litany of health complaints attributed to wind turbines with little or no scientific bases. When you are "told" that you are going to get sick, you become more cognizant of everyday occurrences. (Fasse 2012.) A quick search of the internet produces stressful and often unfounded negative assertions about wind turbines.

Q. Dr. Punch states that, in the 2016 Punch and James Paper, he and his co-author concluded that it is most plausible that "a variety of adverse reactions

are *physiological* effects caused directly or indirectly from exposure to low-frequency sound and infrasound from wind turbines." (Punch Direct, lines 259-61 (emphasis in original).) Do you agree?

A. No. Neither Dr. Punch nor Mr. James is a physician. I do not find it convincing that they can determine the cause of a health complaint simply by evaluating an individual's claim. As I have discussed multiple times herein, there is an established, well-recognized scientific method for conducting this type of research. Dr. Punch has not followed that scientific method.

Q. Dr. Punch states that, "[w]hile psychological expectations and the power of suggestion can influence perceptions of the effects of wind turbine noise on health status, no scientifically valid studies have yet convincingly shown that psychological forces are the major driver of such perceptions." (Punch Direct, lines 261-64.) What is your response?

A. Dr. Punch's statement is not true and demonstrates a lack of basic understanding about the psychological factors associated with human response. Even a cursory review of the literature negates this argument. For example, in a paper published by Enck, et al. 2008 (Exhibit 10), the authors state: "The latest scientific evidence has demonstrated, however, that the placebo effect and the nocebo effect, the negative effects of placebo, stem from highly active processes in the brain that are mediated by psychological mechanisms such as expectation and conditioning."[6] More recently, a paper was published in 2017 exploring the concept that negative expectations result in nocebo (perceived negative) effects.[7] In this paper, the author describes the nocebo effect as the effect of negative expectations.

Q. Dr. Punch states, "I believe that most of these adverse reactions are mediated by disturbances of the hearing and balance mechanisms of the inner ear

[6] Enck P, et al. "New Insights Into the Placebo and Nocebo Responses," Neuron (July 31, 2008): Vol. 59, No. 2, pp. 195–206. (Exhibit 10.)

[7] Colloca, L. 2017. *Nocebo effects can make you feel pain: Negative expectancies derived from features of commercial drugs elicit nocebo effects*. *Science*, 358(6359): 44. (Exhibit 11.)

resulting from the low-frequency noise emitted by industrial wind turbines." (Punch Direct, lines 276-78.) Do you agree?

A. No. Dr. Punch provides no scientific support for his belief. I am not aware of any human data showing that wind turbines have a biological effect on the inner ear.

D. <u>Conclusion Regarding Testimony of Dr. Punch</u>.

Q. What is your overall impression of Dr. Punch's testimony?

A. A review of the peer-reviewed, published data does not support Dr. Punch's general statement about health effects being attributed to the noise of wind turbines. In addition, his attempts to support his opinions about specific mechanisms of adverse health effects that he attributes to wind turbine noise are not reflected in the science related to noise and human hearing or in the numerous reviews of the published scientific works by local, state, national, and international health organizations.

IV. RESPONSE TO TESTIMONY OF RICHARD JAMES

Q. Mr. James references Steven Cooper's Cape Bridgewater study. Are you familiar with this study?

A. Yes. I believe Mr. James is referring to a study performed in Australia in 2014. It was an evaluation of three households (six adults) who had previously lodged multiple complaints with the wind turbine operator relative to noise levels of the Cap Bridgewater Wind Farm. The individuals had reported subjective complaints relative to the wind farm for more than six years prior to participating in the evaluation.

Q. Do you believe that the Cape Bridgewater study supports any conclusion regarding the potential health effects of low frequency sound from wind turbines?

A. No. The Cape Bridgewater study has not been peer-reviewed, and its methodology flaws make the evaluation's results suspect and unreliable:

- Because Mr. Cooper evaluated individuals who have already made complaints about the wind farm, there was a selection bias in who participated in the study. With respect to selection bias, the selection of six individuals who had previously complained about wind turbine operations would have added the effects of recall bias into the study, meaning that the study individuals had already formed an opinion, which would have a direct effect on their reporting of subjective sensations. More simply, individuals who have already reported complaints are more likely to continue to do so.
- The evaluation includes no reference group (or “control group”) to compare the results of the six individuals’ subjective reports. A reference group is the hallmark of an epidemiological study. A researcher cannot reliably evaluate a complaint about turbine operations, or any other stimuli, without having both a group that is exposed to the operations and one that is not to determine if there is a difference in effects that could be attributed to the stimuli.
- In an appropriately designed epidemiological study, the subjects would be “blinded” to the status of the turbines, meaning that they would not know whether the turbines were operational. This did not occur in the Cape Bridgewater study.
- As pointed out by the author of the Cape Bridgewater study, their sample was limited to six individuals who had previously complained – that is, the study was assessing the subjective “sensations” reported by six individuals who feel they have been adversely affected in one way or the other as a result of the wind farm. (Cape Bridgewater study at p. 212.)
- Notably, the correlations reported by the author have not been repeated using a valid epidemiological study design.

Q. Mr. James attaches a document titled *Noise: Windfarms* as Exhibit 2 to his testimony (the "Shepherd Paper"). Are you familiar with the Shepherd Paper?

A. Yes. I note that its authors are all affiliated with the anti-wind group, Society for Wind Vigilance. Specifically, Dr. Hanning is on that group's Board of Directors, and Drs. Shepherd and Thorne are each a "Scientific Advisor."[8]

Q. In your opinion, does the Shepherd Paper provide the Commission with helpful information concerning the Project?

A. No, in the sense that this is a recitation of opinions of individuals who are affiliated with anti-wind groups. As I noted, Drs. Shepherd and Thorne are "Scientific Advisors" for the Society of Wind Vigilance, and Dr. Hanning and Mr. James are on its Board of Directors. That said, there are some thoughtful comments regarding the psychological aspects of annoyance and reported health concerns. However, the term epidemiology and its attribution to a number of reports or opinion pieces is misleading. For example, Dr. Nina Pierpont's work is not a scientific study, and the Shepherd Paper fails to make that clear. The Shepherd Paper's reliance on pieces written by Harry, Pierpont, Krogh, Hanning, Alves-Pereira, and Nissenbaum clearly indicate the slant of the article toward the views of the Society for Wind Vigilance.

Q. The Shepherd Paper states that annoyance is an adverse health effect, relying on the World Health Organization ("WHO"). What is your response?

A. Annoyance is not an adverse health effect, it is a normal physiological response which is deeply rooted in the beliefs, culture, and psychological makeup of the individual. The prevention of annoyance is a worthy but unachievable goal. It is important to recognize that the WHO document that the Shepherd Paper relies upon is from 1999 and does not address wind turbines. Overall, it is an outdated, single reference that does not reflect the current state of the research on this topic. There is peer-reviewed, published research since that time, much of which I have identified

[8] *See* http://www.windvigilance.com/home/advisory-group (last accessed Sept. 24, 2018).

in my testimony, that provides more reliable and relevant information for the Commission.

In addition, importantly, the WHO document that the Shepherd Paper relies upon defines annoyance broadly as "a feeling of displeasure associated with *any* agent or condition, known *or believed* by an individual or group to adversely affect them."[9] I further note that the WHO document discussed annoyance in terms of a social/behavioral effect and states: "it should be recognized that equal levels of different traffic and industrial noises cause different magnitudes of annoyance. This is because annoyance in populations varies not only with the characteristics of the noise, including the noise source, but also depends to a large degree on many non-acoustical factors of a social, psychological, or economic nature."[10]

Q. The Shepherd Paper notes that some individuals describe themselves as "noise sensitive." What is your response?

A. That phrase, as used in the Shepherd Paper, is not a recognized specific health condition in medical literature. It is neither an illness nor a disease but more likely a conditioned response. In lay terms, this might be described as a state of mind. As I discussed previously regarding the nocebo effect, if a person does not like something, he or she is more likely to have a negative response to any situation reflective of the stimulating event.

Q. Are you familiar with the Shirley Wind Project study by Dr. Schomer referred to by Mr. James?

A. Yes.

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[9] WHO, *Guidelines for Community Noise*, at 32 (1999).

[10] *Id.* at xi; *see also id.* at 33 and 42 ("[A]nnoyance reactions are sensitive to many non-acoustical factors of social, psychological or economic nature, and there are also considerable differences in individual reactions to the same noise.").

Q. Do you believe that Dr. Schomer's study provides helpful information to the Commission with respect to this Project?

A. No. The study did not use study methods such that specific conclusions could be scientifically supported. It also did not demonstrate a causal relationship between the wind farm and the health complaints reported by some residents.

Q. Mr. James asserts that you are "not qualified to speak to the issue of acoustics or human response to wind turbine noise." (James Direct, lines 398-99.) What is your response?

A. I will be the first to admit that I am not an acoustician. I am, however, a graduate trained epidemiologist with 30 years of experience working in public health and 20 of those years working in the areas of occupational and environmental medicine as a Board Certified Physician. I am using this experience and training to assess the health and exposure claims made by persons who are attributing various health conditions to wind turbine noise.

V. CONCLUSION

Q. After reviewing the testimonies of Prof. Alves-Pereira, Dr. Punch, and Mr. James, do you still hold the opinions offered in your Supplemental Direct Testimony?

A. Yes. My opinions are based on peer-reviewed, published literature, and Dr. Alves-Pereira, Dr. Punch, and Mr. James did not present any testimony based on similarly reliable research. It is important to acknowledge that there have been more than 400 gigawatts of wind power generation installed around the world,[11] and Prof. Alves-Pereira, Dr. Punch, and Mr. James base their opinions largely only on a small number of self-reported complaints. As such, my opinions remain unchanged.

[11] *See* https://www.worldenergy.org/data/resources/resource/wind/ (last accessed Sept. 24, 2018).

Q. Does this conclude your Rebuttal Testimony?

A. Yes.

Dated this 26th day of September, 2018.

Dr. Mark Roberts

64899496

EXHIBIT A5-1

LUBW

Landesanstalt für Umwelt, Messungen und
Naturschutz Baden-Württemberg

Low-frequency noise incl. infrasound from wind turbines and other sources

Report on results of the measurement project 2013-2015

Baden-Württemberg

LUBW
Landesanstalt für Umwelt, Messungen und
Naturschutz Baden-Württemberg

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PRINCIPAL

Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg
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(State Office for the Environment, Measurement and Nature Conservation
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P. O. Box 10 01 63, 76231 Karlsruhe
Internet: www.lubw.baden-wuerttemberg.de

EDITORS

U. Ratzel, O. Bayer, P. Brachat, M. Hoffmann, K. Jänke,
K.-J. Kiesel, C. Mehnert, Dr. C. Scheck
LUBW Department 34 – Technischer Arbeitsschutz, Lärmschutz
(Technical Occupational Safety, Noise Protection)
Contact: windenergie@lubw.bwl.de

Dr. C. Westerhausen, Dr. K.-G. Krapf, L. Herrmann, J. Blaul
Wölfel Engineering GmbH + Co. KG, Höchberg

Wölfel

ENGLISH TRANSLATION

CL-Communication GmbH, 41199 Mönchengladbach

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1 Background and introduction

There are currently (as of 31.12.2015) 445 wind turbines in operation in Baden-Wuerttemberg and 100 more under construction [1]. In the coming years many more will be added to that number. When it comes to the expansion of wind energy, the effects on humans and the environment need to be taken into account. Wind turbines make noise. In addition to the usual audible sound, they also generate low-frequency sounds or infrasound, i.e. extremely low tones.

Infrasound is described as the frequency range below 20 hertz (for explanations of important technical terms, please refer to Appendix A3). From a physical point of view, these noises are generated particularly through aerodynamic and mechanical processes, e.g. the flow around rotor blades, machine noise or the vibration of equipment components. Our hearing is very insensitive to low-frequency noise components. The wind energy decree of Baden-Wuerttemberg [1] includes, among other things, regulations and statements to protect the population against low-frequency noise and infrasound. However, within the scope of wind energy development, fears are commonly expressed that this infrasound may affect people or jeopardize their health.

In September 2012, the LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Wuerttemberg presented the concept for a measuring project, with which current data on low-frequency noise incl. infrasound from wind turbines and other sources was to be collected. As a result, the LUBW was entrusted with the implementation of the project by the Ministry of Environment, Climate and Energy Baden-Wuerttemberg. The company Wölfel Engineering GmbH + Co. KG was taken on board as a supporting measuring institute. The detailed planning and work was thus begun together at the beginning of 2013.

Within the project, numerous measurements near wind turbines and other sources as well as the associated analyses and evaluations were carried out. The results obtained are summarized in this measurement report. The LUBW wishes to use it as a contribution towards providing objectivity to the discussion. The report is aimed at the interested public as well as administrative bodies and professionals.

At this point we would like to thank all participants for enabling the measurements as well as the friendly support during the implementation, in particular the operators of wind turbines, the involved administrative authorities in Baden-Wuerttemberg and Rhineland-Palatinate, the State Museum of Natural History Karlsruhe and the Education Authority of Karlsruhe. The Bavarian State Office for the Environment and the State Office for the Environment, Nature Conservation and Geology Mecklenburg-Western Pomerania were kind enough to provide a number of pictures.

1) The terms "wind power plant" and "wind turbine" are synonymous. For our measurement project we have used the term "wind turbine" in the title. The German term is embedded in immissions law (fourth regulation on the implementation of the Federal Immission Control Act – Regulation on licensing requirements Appendices – 4. BImSchV, Appendix 1 no. 1.6.1 [2] [3]). In the text of this report the common term "wind power plant" may also be used.

2 Summary

In cooperation with Wölfel Engineering GmbH + Co. KG, the LUBW carried out the measurement project "Low-frequency noise incl. infrasound from wind turbines and other sources", which began in 2013. This report provides information on the results of the measurement project.

The aim of the project is to collect current data on the occurrence of infrasound (from 1 Hz) and low-frequency noise in the area of wind turbines and other sources. For this purpose, measurements were taken up to the end of 2015 in the areas around six wind turbines by different manufacturers and with different sizes, covering a power range from 1.8 to 3.2 megawatts (MW). Depending on local conditions, the distances to the wind turbines were approx. 150 m, 300 m and 700 m. The results of the measurements at the wind turbines are described and illustrated by means of graphs in Chapter 4. In addition to the acoustical analyses, vibration measurements were performed in the vicinity of a wind power plant in order to determine possible vibration emissions of the power plant on the environment. The procedure and the difficulties encountered are explained accordingly.

Since road traffic is also considered to be a source of infrasound and low-frequency noise, it stood to reason to extend the measurement project to cover that too. Chapter 5 provides results of measurements at an urban road, which took place both outside as well as inside a residential building. In addition, the data from the LUBW measurement stations for road traffic noise in Karlsruhe and Reutlingen were analysed and illustrated with respect to low-frequency noise and infrasound. Furthermore, results of own measurements at a motorway are also illustrated. This is supplemented by data from sound level measurements inside a moving car.

Measurements without reference sources during the day and at night took place in the centre of Karlsruhe on the Friedrichsplatz. At the same time, measurements were also taken on the roof of the natural history museum and in an interior room of the education authority (Chapter 6). Typical noise occurring in residential buildings through widespread technical equipment, such as washing machines, refrigerators or heating equipment, was also recorded and is presented in Chapter 7. In order to enable statements about natural sources of infrasound, measurements were taken on an open field, near a forest and in a forest. The measurement of low-frequency sound through sea surf is also introduced based on literature (Chapter 8). In Chapter 9, considerations are made for a monitoring station for the continuous monitoring of low-frequency noise incl. infrasound. Such an independently operating permanent measuring station could possibly be used when it comes to complaint cases.

The report at hand extends the previous interim report through further findings and contains a multiplicity of measurement results. It is aimed at both professionals as well as the interested general public. Great interest for our analyses was shown by the public and administrative bodies during the entire duration of the project. SWR TV even aired a report about the measurements. The LUBW will continue to pursue the issue in the future.

In addition to general information about infrasound, the appendices provide extensive explanations of technical terms and the technology used, as well as information on the sources.

Figure 2-1: *Wind turbines – how much infrasound do they emit? Photo: Wölfel company*

Figure 2-2: *Impressions of the measurements during the execution of the measurement project. a) Construction of a wind measuring mast (top left) and b) of a measurement point (top right) during measurement at a wind turbine. c) and d) Setup of measurement points in the city centre of Karlsruhe (bottom). Photos: LUBW*

RESULTS

In summary, the measurements lead to the following findings:

- The infrasound being emanated from the wind turbines can generally be measured well in the direct vicinity. Discrete lines occur below 8 Hz in the frequency spectrum, which are attributed to the uniform movement of the individual rotor blades.

- For the measurements carried out even at close range, the infrasound level in the vicinity of wind turbines is – at distances between 120 m and 300 m – well below the threshold of what humans perceive in accordance with DIN 45680 (2013 Draft) [5] or ***Table A3-1***.

- At a distance of 700 m from the wind turbines, it was observed by means of measurements that when the turbine is switched on, the measured infrasound level did not increase or only increase to a limited extent. The infrasound was generated mainly by the wind and not by the turbines.

- The determined G-weighted levels [2)] at distances between 120 m and 190 m were between 55 dB(G) and 80 dB(G) with the turbine switched on, and between 50 dB(G) and 75 dB(G) with the turbine switched off. At distances of 650 m and 700 m, the G-levels were between 50 dB(G) and 75 dB(G) for both turbines switched

2) The G-level – expressed as dB(G) – represents a frequency-weighted single value of the noise in the low-frequency and infrasound range. The human ear is insensitive to any influences in this frequency range (for definition and measurement curve see Appendix A3).

on as well as off, see ***Table 2-1***. The large fluctuations are caused, among other things, by the strongly varying noise components due to the wind, as well as various different surrounding conditions.

- The infrasound and low-frequency noise measured in the vicinity of operating wind turbines consists of a proportion that is generated by the wind turbine, a proportion that occurs by itself in the vicinity due to the wind, and a proportion that is induced by the wind at the microphone. In this case the wind itself is thus always an "interference factor" when determining the wind turbine noise. The measured values are therefore subject to a wide spread.

- The vibrations caused by the wind turbine being examined were already minimal at a distance of less than 300 m. At distances provided for residential areas alone due to noise protection issues, no relevant effects are to be expected for residential buildings.

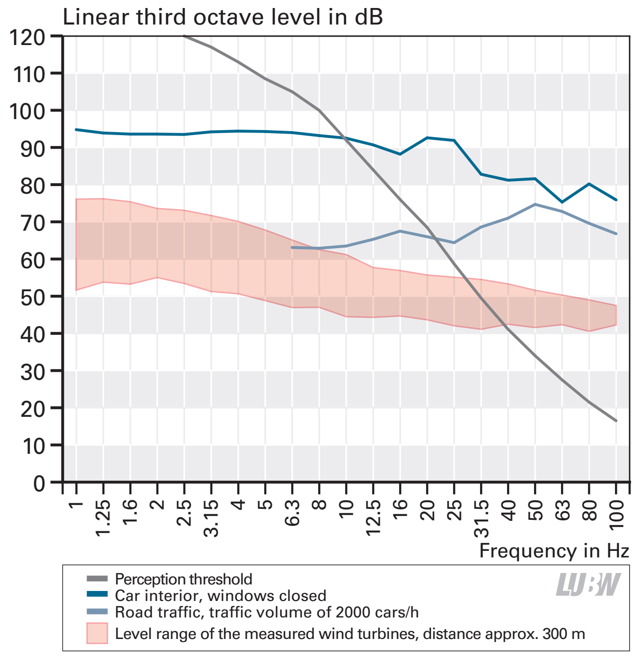


Figure 2-3: *Comparison of road noise inside and outside of motor vehicles with the level range of wind turbines at a distance of approx. 300 m as well as the perception threshold according to Table A3-1 regarding infrasound and low-frequency noise. For measuring corrections, see Section 4.1.*

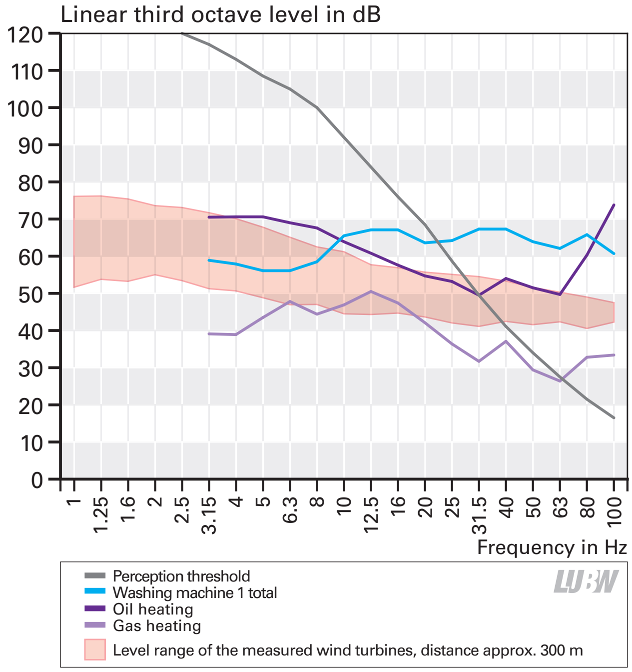
- It was possible to carry out the measurements for the low-frequency noise incl. infrasound resulting from road traffic during times without interfering wind noise. Contrary to the case with wind turbines, the measured levels also occur directly in areas with adjacent residential buildings. As expected, it was observed that the infrasound and low-frequency noise levels fell at night. Clear correlations with the amount of traffic were also ascertained. The higher the amount of traffic, the higher the low-frequency noise and infrasound levels.

- The infrasound noise levels of road traffic in the area of residential buildings in the vicinity in the individual third octave bands were a maximum of approx. 70 dB (unweighted), while the G-weighted level was in the range between 55 dB(G) and 80 dB(G).

- When it comes to the immission measurements of road traffic noise, increased levels in the area between approx. 30 Hz and 80 Hz were ascertained in the frequency spectra. The low-frequency noise in this area lies well above the perception threshold according to ***Table A3-1*** and is therefore more relevant with regards to its effect than the subliminal infrasound levels below 20 Hz. The levels of low-frequency noise in the observed situations of road traffic are significantly higher than in the vicinity of wind turbines (***Table 2-1***).

- The measurements in the city centre of Karlsruhe (Friedrichsplatz) showed that the G-weighted levels dropped from 65 dB(G) during the day to levels of around 50 dB(G) at night. Wind noise played no role for these measurements. Relatively high third octave levels up to 60 dB (unweighted) could be observed between 25 Hz and 80 Hz, probably deriving from traffic noise, even though the Friedrichsplatz is not located directly on a busy road.

- The highest levels in the context of the measurement project were measured in the interior of a mid-range car travelling at 130 km/h. Even though these are not immission levels that occur in a free environment, they are an everyday situation that many people are frequently subjected to for a longer period of time. The measured values for both the infrasound as well as the other



***Firgure 2-4**: Comparison of noise of technical appliances in residential buildings with the level range of wind turbines at a distance of approx. 300 m as well as the perception threshold according to Table A3-1 regarding infrasound and low-frequency noise. For measuring corrections, see Section 4.1.*

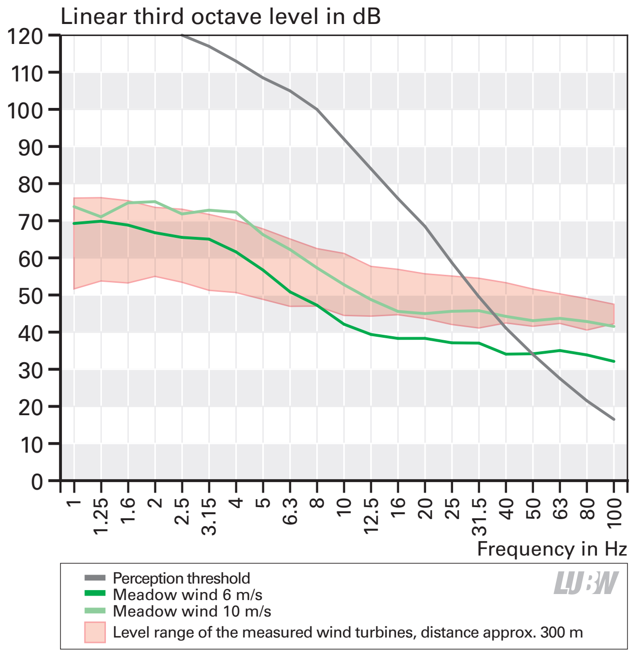


***Figure 2-5**: Comparison of noise situation in an open field (without source reference) with the level range of wind turbines at a distance of approx. 300 m as well as the perception threshold according to Table A3-1 regarding infrasound and low-frequency noise. For measuring corrections for wind turbines, see section 4.1.*

low-frequency areas are higher by several orders of magnitude than the values measured in road traffic or at the wind turbines.

- The measurement of appliances in a residential building showed the highest infrasound levels during the spin cycle of washing machines. In individual third octaves the levels reached the perception threshold according to ***Table A3-1***. As expected, it turned out that building components deaden higher-frequency noise significantly better than the low frequencies below 20 Hz.

- In a rural area, the spectral distribution of noise on an open field, the edge of a forest, in a forest with wind is in principle similar to in the vicinity of a wind turbine (***Figure 2-5***). For open fields, linear levels that are up to 30 dB higher than in a forest can be seen in the narrowband spectrum. Above 16 Hz, the differences are no longer as pronounced. Higher levels occur for A-weighted audible sound in the forest, which is attributable to the rustling of leaves.

CONCLUSION

Infrasound is caused by a large number of different natural and technical sources. It is an everyday part of our environment that can be found everywhere. Wind turbines make no considerable contribution to it. The infrasound levels generated by them lie clearly below the limits of human perception. There is no scientifically proven evidence of adverse effects in this level range.

The measurement results of wind turbines also show no acoustic abnormalities for the frequency range of audible sound. Wind turbines can thus be assessed like other installations according to the specifications of the TA Lärm (noise prevention regulations). It can be concluded that, given the respective compliance with legal and professional technical requirements for planning and approval, harmful effects of noise from wind turbines cannot be deduced.

Table 2-1*: Comparative overview of results. The readings were often subject to considerable fluctuations. Here they were rounded to the nearest 5 dB, some are based on different averaging times. More information can be found in the relevant sections of the report. To enable a comparison of the results (measurements with/without reverberant plate) a correction was carried out; for more information see Section 4.1.*

Source/situation	Section	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB [1]	Low-frequency third octave levels 25-80 Hz in dB [1]
Wind turbines [2]		**WT on / off**	**WT on**	**WT off**
– WT 1	4.2	700 m: 55-75 / 50-75 150 m: 65-75 / 50-70	– 150 m: 55-70	– 150 m: 50-55
– WT 2	4.3	240 m: 60-75 / 60-75 120 m: 60-80 / 60-75	– 120 m: 60-75	– 120 m: 50-55
– WT 3	4.4	300 m: 55-80 / 50-75 180 m: 55-75 / 50-75	– 180 m: 50-70	– 180 m: 45-50
– WT 4	4.5	650 m: 50-65 / 50-65 180 m: 55-65 / 50-65	– 180 m: 45-55	– 180 m: 40-45
– WT 5	4.6	650 m: 60-70 / 55-65 185 m: 60-70 / 55-65	– 185 m: 50-65	– 185 m: 45-50
– WT 6	4.7	705 m: 55-65 / 55-60 192 m: 60-75 / 55-65	– 192 m: 55-65	– 192 m: 45-50
Road traffic				
– Würzburg inner city, balcony [3] – Würzburg inner city, living quarter [3]	5.1	50-75 40-65	35-65 20-55	55-75 35-55
– Karlsruhe, noise measurement station [3]	5.2	65-75	45-65	55-70
– Reutlingen, noise measurement station [3]	5.2	70-80	50-70	55-75
– Motorway A5 near Malsch, 80 m [4] – Motorway A5 near Malsch, 260 m [4]	5.3	75 70	55-60 55-60	60-70 55-60
– Interior noise in passenger car 130 km/h [4] – interior noise in minibus at 130 km/h [4]	5.4	105 100	90-95 85-90	75-95 80-90
Urban background, Karlsruhe [3] – roof of natural history museum – Friedrichsplatz – Interior	6	50-65 50-65 45-60	35-55 35-50 20-45	up to 60 up to 60 up to 55
Noise sources in residential buildings [5]				
– Washing machine (all operating modes)	7.1	50-85	25-75	10-75
– Heating (oil and gas, full load)	7.2	60-70	40-70	25-60
– Refrigerator (full load)	7.2	60	30-50	15-35
Rural environment [6]		**Wind 6 / 10 m/s**	**Wind 6 / 10 m/s**	**Wind 6 / 10 m/s**
– open field, 130 m from forest	8.1	50-65 / 55-65	40-70 / 45-75	35-40 / 40-45
– Edge of forest	8.1	50-60 / 50-60	35-50 / 45-75	35-40 / 40-45
– Forest	8.1	50-60 / 50-60	35-40 / 40-45	35-50 / 35-40
Sea surf				
– Beach, 25 m away	8.2	75	55-70	not reported
– Rock cliff, 250 m away	8.2	70	55-65	not reported

1) Linear third octave level (unweighted)
2) For wind turbines: From 10-second values (see illustrations of the G-level depending on the wind speed)
3) For road traffic (Würzburg) and urban background (Karlsruhe): From averaging levels over an hour
4) For federal motorway and car interior level: From averaging over several minutes
5) For noise sources in residential building: From averaging levels of typical operating cycles
6) The wind measurement was always carried out at the measurement point MP1 (open field).

3 Scope of analysis

The scope of analysis includes the following measurements and examinations:

- Measurement of low-frequency noise, including infrasound, from 1 Hz at a total of six different wind turbines at a distance of approx. 150 m, 300 m and 700 m respectively (if possible). In the process, the turbines were each turned on and off. The distances roughly correspond to the set reference intervals for emission measurements at close range (approx. 150 m), a roughly double distance in the immediate vicinity (approx. 300 m) and a distance that can occur for real noise immissions (700 m, see also planning information in the wind energy statute of Baden Wuerttemberg [1]).

- Comparative measurement of the noise immission in the sphere of influence of a road both outside as well as inside a residential building.

- Determination of low-frequency effects from 6.3 Hz of road traffic on the permanent monitoring stations in Karlsruhe and Reutlingen as well as at the A5 motorway near Malsch at different distances.

- Measuring of the infrasound levels within a passenger car travelling at 130 km/h.

- Determination of the urban background through a comparative measurement of the noise situation in Karlsruhe (Friedrichsplatz) without specific source reference both outside as well as inside a building.

- Comparative measurement of the noise situation in a rural area without a concrete source reference.

- Measurement of oscillations (vibrations) in the ground in the vicinity of a wind turbine.

- Elaboration of a feasibility concept for the conception of a self-sufficient permanent measuring station for low frequency noise incl. infrasound, in order to possibly measure the effects over a longer period of time (e.g. several weeks).

The following planned steps of the project have not yet been completed:

- Measurement of the direction dependency in the low-frequency frequency range based on four measurement points around a wind turbine. – This is where technical problems occurred during the measurement. They therefore have to be repeated.

- Measurement of low-frequency noise, including infrasound, from 1 Hz at a wind farm, incl. indoor measurement in a residential building at a distance of approx. 700 m to the nearest turbine. The wind turbines are switched on and off in the process. – The necessary meteorological conditions did not occur at the planned measuring location since commissioning in August 2014. It was therefore not possible to carry out a standard-compliant measurement. The measurement is to be carried out at a later date.

4 Wind turbines

The results of the six measurements that took place in the context of this project at wind turbines in Baden-Wuerttemberg, Rhineland-Palatinate and Bavaria are presented in the following (***Table 4-1***). The measurements were carried out by Wölfel Engineering GmbH + Co. KG, Höchberg, on behalf of the LUBW. The graphical representations of the emissions and immissions in the low-frequency range, both with the turbines switched on and off, are an integral part. The third octave levels enable a comparison with the human perception threshold. The A and G-weighted sound pressure levels are represented depending on the wind velocity for three different distances from the turbine. The A-weighted sound level – specified as dB(A) – simulates the human hearing sensitivity. The G-level – specified as dB(G) – represents a singular value, which rates only infrasound and parts of the low-frequency frequency range. The human ear is very insensitive to these frequency ranges (for more info please refer to ***Figure A3-1*** in Appendix A3). Additionally recorded narrow band spectra, all specified with a resolution of 0.1 Hz, are able to depict more clearly specific features of the noise characteristics of wind turbines. The level values in a spectrum depend on the selected resolution. Therefore, narrow band levels cannot be compared with third octave levels. Only third octave levels are suitable for comparisons with the hearing threshold, as it also corresponds to third octave levels.

All the following results of measurements on operating wind turbines also include the noise caused by the wind itself in the vicinity. In addition, in the case of strong wind, noise will inevitably be induced at the microphones despite the use of double wind screens. Therefore, the results of a measurement cannot be attributed to the respective wind turbine alone. The differences shown by the comparison of situations with the turbine switched on and off are therefore all the more important. When it comes to the noise measurements at roads (Chapter 5) and in the city centre (Chapter 6), the effects related to the wind are irrelevant. Thus, the measuring results for wind turbines and roads designate different situations, which cannot be directly compared with one another.

The selection of the wind turbines that were to be measured proved to be rather difficult. The initial contacts with operators were kindly set up by the Baden-Wuerttemberg approval authorities (district offices) after the LUBW had carried out a corresponding query. The participation of the turbine operators was on a voluntary basis. Some operators had concerns about participating in the project.

First, the locations were qualified from an acoustic perspective. Sites near busy roads, or other disruptive noise sources – including forests – were deemed unsuitable and thus rejected. Regarding more powerful turbines, the site search had to be extended by the LUBW to include Rhineland-Palatinate. In this case constructive support was also provided several times by the authorities. Not only weather-related restrictions had to be coped with (matching wind directions and wind speeds; strong winds resulting in termination of measuring due to automatic shutdown; snowfall in the vicinity) during the project. One wind power plant broke down shortly before the measurement and was

Table 4-1*: Overview of the wind power plants where measurements were carried out in the context of this project. The individual power plants and the associated results are described in more detail in Sections 4.2 to 4.7.*

Wind turbine (WT)	WT 1	WT 2	WT 3	WT 4	WT 5	WT 6
Manufacturer Model	REpower* MM92	Enercon E-66	Enercon E-82	REpower* 3.2M114	Nordex N117/2400	Enercon E-101
Nominal capacity	2.0 MW	1.8 MW	2.0 MW	3.2 MW	2.4 MW	3.05 MW
Rotor diameter	92 m	70 m	82 m	114 m	117 m	101 m
Hub height	100 m	86 m	138 m	143 m	140.6 m	135.4 m

* Senvion since 2014

inoperable for a longer period of time. One operator withdrew his consent to the measurement as the proposed turbine had difficulties with the acceptance inspection. A construction site was set up in the vicinity of another wind turbine, which caused background noise and thus made the measurement of the turbine noise impossible. This is just to show some of the challenges that had to be overcome during the project. The delays that were thus incurred were not foreseeable from the start.

***Figure 4-1**: Model type WT 1, REpower MM92*

***Figure 4-2**: Model type WT 2, Enercon E-66*

***Figure 4-3**: Model type WT 3, Enercon E-82*

***Figure 4-4**: Model type WT 4,* REpower 3.2M114

***Figure 4-5**: Model type WT 5,* Nordex N117/2400

***Figure 4-6**: Model type WT 6,* Enercon E-101

These images convey an impression of the examined wind power plants, covering the common power range between 1.8 MW and 3.2 MW. The hub height varies between 86 m and 143 m, the rotor diameter varies between 70 m and 117 m. Photos: batcam.de (left column), LUBW (Fig. 4-2 and 4-4), Lucas Bauer wind-turbine-models.com (Fig. 4-6)

4.1 Measurements and evaluations

The noise measurements were carried out according to DIN EN 61400-11 [6] and the technical guidelines for wind turbines [7] respectively. Furthermore, the noise immissions in the frequency range from 1 Hz were measured and further guidelines [8] [9] used if necessary.

These regulations describe noise measurement methods for determining the sound emissions of a wind turbine. They establish the procedures for the measurement, analysis and presentation of results of noise emitted by wind turbines. Likewise, requirements for the measuring devices and calibration are provided in order to ensure the accuracy and consistency of the acoustic and other measurements. This is where special microphones that can be applied from levels of 1 Hz onwards were used. The non-acoustic measurements that are necessary in order to determine the atmospheric conditions that are relevant for the determination of the noise emission are also described in more detail. All the parameters that are to be measured and illustrated, as well as the necessary data processing to determine these parameters are defined. For more details on measurement techniques, please refer to Appendix A4.

Based on the measurements, which – if possible – should be made at distances of approx. 150 m, 300 m and 700 m from the turbine (it was not always possible to observe these distances exactly), statements about emissions and immissions of the turbines can be made. The wind turbines that were to be measured were each operated in open operating mode, where the system is geared towards performance optimization. Experience has shown that the highest noise levels can be expected in this mode.

Over the entire measurement time, both third octave as well as octave bandwidths in the frequency range of 6.3 Hz to 10 Hz were formed and stored with the sound level meters used (see Appendix A4). From the recorded audio files, third octave and octave spectra were formed in the range of 1 Hz to 10 kHz as well as narrowband spectra in the range of 0.8 Hz to 10 kHz by means of digital filters. Times with extraneous noise were marked during the measurements and not used for the evaluations. The microphones were each mounted on a reverberant floor plate and provided with a primary and secondary wind screen (see ***Firgure 4.3-1***), in order to reduce or even avoid wind noise induced at the microphone. The use of a reverberant plate results in a doubling of sound pressure at the microphone, resulting in higher readings. When determining the sound power level, a correction of -6 dB therefore has to be undertaken afterwards. The correction was carried out in this report for the presentation of measured values only in the case of a comparison of results that emerged through different measuring arrangements (see ***Firgures 2-3 to 2-5*** as well as ***Table 2-1***) or comparisons with the perception threshold, e.g. in ***Figure 4.2-5***.

For some representations of the measuring results, the human perception threshold was inserted into the graphics as a comparison. This is where we used the values of DIN 45680 (2013 draft) [5]. These values are somewhat lower than those of the currently valid DIN 45680 (1997) [4] that are to be applied in accordance with the TA Lärm [10]. Below 8 Hz, the values of the standard work were supplemented by data from literature [11], see ***Table A3-1***. Further information is listed in Appendix A1 for the difficulties regarding the hearing and perception threshold. Graphical comparisons of the hearing and perception threshold are also presented there (***Figure A1-2***).

In addition to the sound level measurements, vibration measurements were also carried out at the foundation of wind turbine 5, and at distances of 32 m, 64 m and 285 m (see Section 4.8).

4.2 Noise at wind turbine 1: REpower MM92 – 2.0 MW

BASIC CONDITIONS

The wind turbine 1 (WT 1) is a power plant made by the company Repower, model MM92/100 (***Figure 4-1***) with a nominal generator capacity of 2.05 MW at a wind speed of 12.5 m/s at hub height. The rotor diameter is 92 m, the hub height above ground is 100 m. The immediate vicinity of the wind turbine is defined by agricultural land with individual trees scattered around. Adjacent to it are areas with conifer tree culitvation and forest. Further wind power plants are located in the wider vicinity of the wind turbine

Figure 4.2-1*: Wind measurement mast with view in direction of the wind power plant being measured. Photo: Wölfel company*

being measured. These were switched off during the measurement period. A path in close proximity is allowed to be used only by agricultural traffic and is used only seldom. The measurements were carried out on 11.04.2013 between 8:00 a.m. and 4:00 p.m. The position of the microphone at the measurement point MP1 was at a distance of 150 m to the power plant in a downwind direction. This was in order to take into account the worst case scenario (support of sound propagation through the wind). Further measurement points MP2 and MP3 were located at intervals of 300 and 700 m in a downwind direction. ***Figure 4.2-1*** provides an impression. The measurement was carried out in a wind speed range of 5 to 14 m/s, a temperature range of 10 to 12 °C and an atmospheric pressure range of 946 to 951 hPa. The entire power range of the power plant was covered up to the nominal power. The turbulence intensity, which is basically a measure of the gustiness of the wind (see Appendix A3), was 18 %.

RESULTS: NARROW BAND LEVEL

Figure 4.2-2 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 150 m with a resolution of 0.1 Hz. The wind speed was 6.5 m/s. With the power plant switched on, six discrete maxima can be clearly seen in the infrasound range between 1 Hz and 5.5 Hz. This concerns infrasound generated by the rotor due to its motion. The measured frequencies correspond to the passage frequency of a rotor blade of approximately 0.75 Hz, which corresponds with a frequency of the rotor of 15 rpm and the harmonic overtones at 1.5 Hz, 2.2 Hz, 3.0 Hz, 3.7 Hz, 4.5 Hz and 5.2 Hz (***Figure 4.2-2***). Further maxima were measured at 25 Hz and

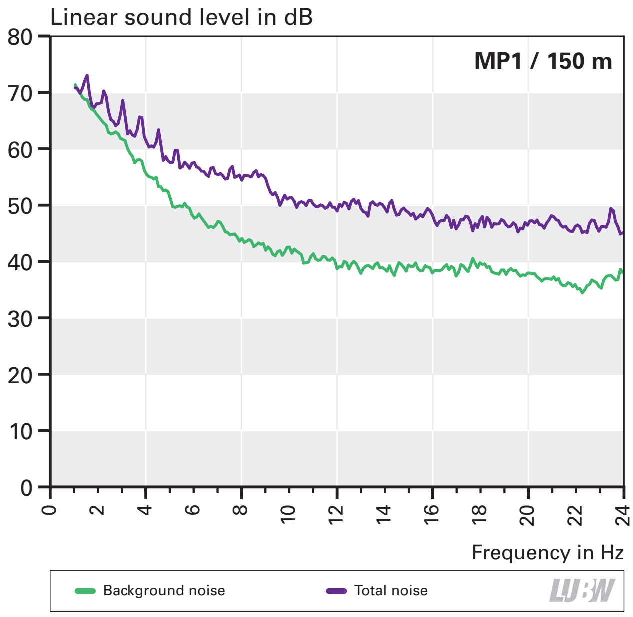


Figure 4.2-2*: Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 1 for the frequency range of infrasound*

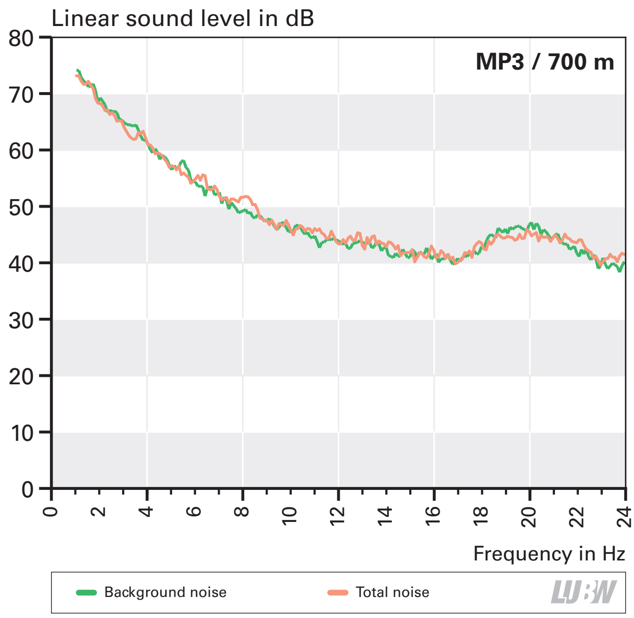


Figure 4.2-3*: Narrow band spectra of background noise and total noise at a far range from the wind turbine WT 1 for the frequency range of infrasound*

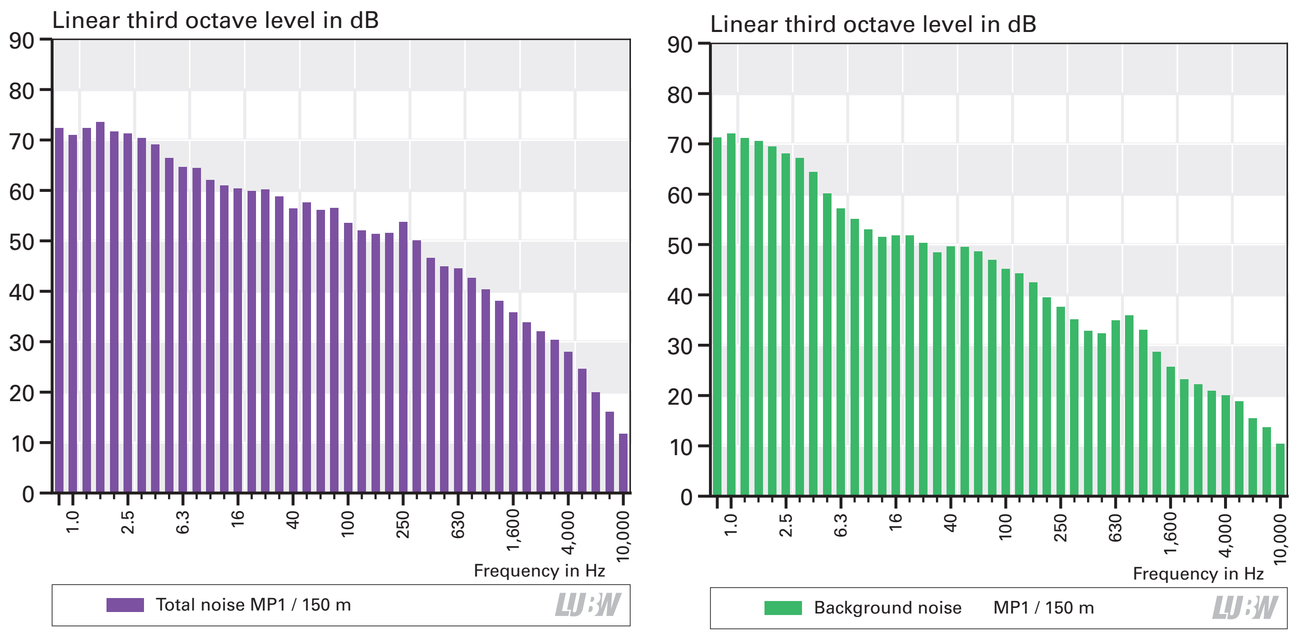


***Figure 4.2-4**: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 1*

50 Hz, These are at a much lower level, and are attributable to the operation of the generator. The peaks disappear when the power plant is switched off.

Figure 4.2-3 shows the narrow band spectra of background noise and overall noise at the measurement point MP3 at a distance of 700 m. At this distance, no discrete infrasound maxima can be distinguished anymore when the power plant is on. There were no measurable differences in infrasound between the conditions "turbine on" and "turbine off" for this measurement at a distance of 700 m. This was apparently caused by the noise of wind and the surroundings. Here too, the wind speed was 6.5 m/s.

RESULTS: THIRD OCTAVE LEVEL

Figure 4.2-4 shows the third octave spectra of background noise and overall noise at the measurement point MP1 (150 m) for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 6.5 m/s. The level reduction due to the shutdown of the power plant is visible here in a considerably broader spectral range.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.2-5 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP3 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was

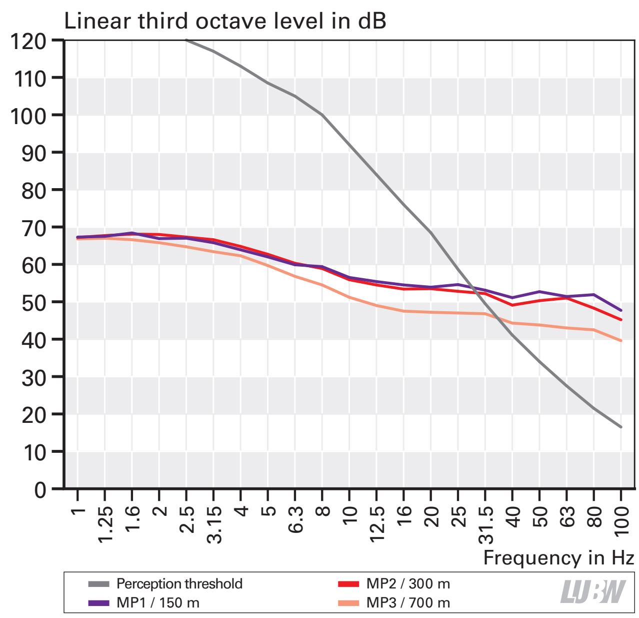


***Figure 4.2-5**: Third octave spectra of total noise at the measurement points MP1 (150 m), MP2 (300 m) and MP3 (700 m) of WT 1, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

6.8 m/s. It must be kept in mind that the background noise of wind and vegetation are also included. These may vary at the respective measurement point. It is apparent that from about 6-8 Hz the overall noise becomes less with increasing distance to the power plant. The differences become clearer with increasing frequency. In terms of audible sound, this constitutes an audible effect. At the measurement point located at a distance of 700 m, the turbine is no longer constantly and at most only slightly noticeable; the curve is almost the same as for the background noise. In the infrasound range, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

The above charts reflect a concrete individual situation at a given wind speed (6.5 or 6.8 m/s respectively) as an example. However, the results were presented at different frequencies. Of course this is where the question arises as to what the relationships are like at different wind speeds. These were also measured, and the results are shown in ***Figure 4.2-6***. This figure is not easy to understand straight away and should therefore be explained step by step.

The three graphs represent the relationships at the respective measurement points at a distance of 150 m (upper figure), 300 m (middle figure) and 700 m (lower figure). The wind speed of 4.5 to 10.5 m/s is placed on the bottom, horizontal axis. The vertical axis represents the sound level values. Each point corresponds to a single measurement sequence of 10 seconds at a given wind speed. Violet dots, which depict the lower value area, represent audible sound with the turbine on, expressed in dB(A). It is easy to see at distances of 150 and 300 m that the audible sound increases slightly at wind speeds of 4.5 m/s up to just above 5.5 m/s, but then remains constant at higher wind speeds. How does this behave with low-frequency sound or infrasound respectively? In order to find out, the dependency of the G-weighted sound level, specified as dB(G), was examined.

The red dots represent the G-weighted sound level when the turbine is switched on, the green dots when the turbine is switched off. In the vicinity of the power plant, at a distance of 150 m (upper image), you can see clearly that the sound level is similarly dependent on the wind speed also in the low-frequency range (incl. infrasound) as is the case for audible sound when a power plant is switched on. Furthermore, it is also visible that there is a clear difference between the turbine being on and the turbine being off. The G levels are significantly higher when the turbine is on (red dots) than when it is switched off (green dots). At a distance of 300 m (middle image) this difference is already less pronounced, and at 700 m it is no longer recognizable. There is virtually no difference anymore between the red cluster of dots (turbine on) and the green cluster of dots (turbine off), regardless of the wind speed.

These readings also show clearly that the background noise through wind and vegetation, measured when the turbine is switched off (green dot cluster), is subject to strong scattering, i.e. particularly noticeable natural fluctuations. The values span a range of up to 20 dB(G). The measured sequences of the turbine noise, on the other hand, scatter significantly less, at least in the near-field.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.2-7 shows the A and G-weighted level curves between 11:00 a.m. and 3:00 p.m. at a distance of 150 m and 700 m. In addition, the operating conditions of the wind turbine (green = turbine on, light blue = turbine off) as well as periods of time with external noise (violet) are depicted. For the two level developments of measurement point MP1, the operational phase "turbine off" is easily recognisable through the considerably declining level developments. At the measurement point MP3, a drop in the level with the turbine turned off is barely distinguishable due to the fluctuating background noise – only the minima of the A level development are slightly lower than when the turbine is on. The G level development, however, covers nearly the same range of values as when the turbine is switched off.

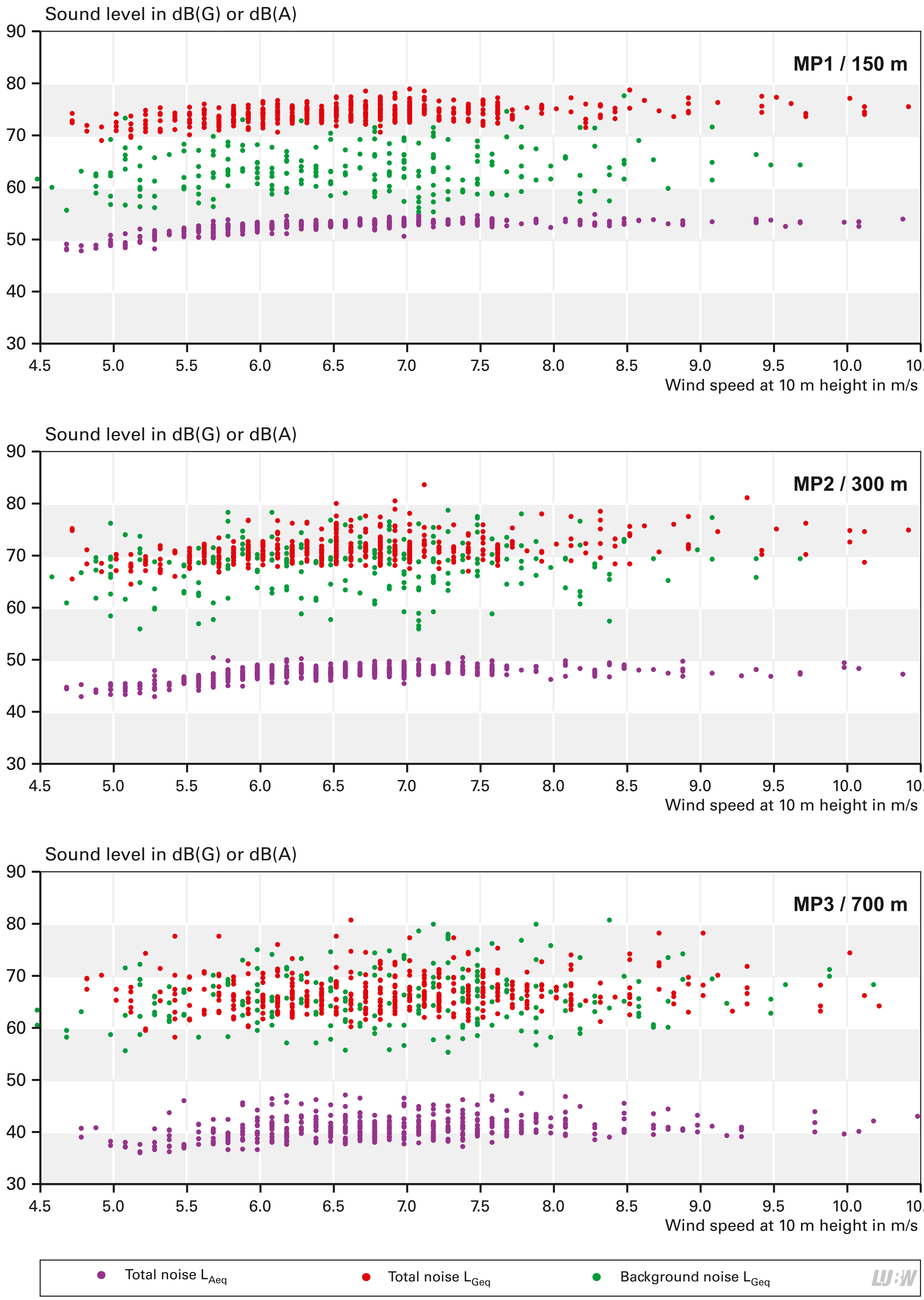


Figure 4.2-6: *Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 1. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

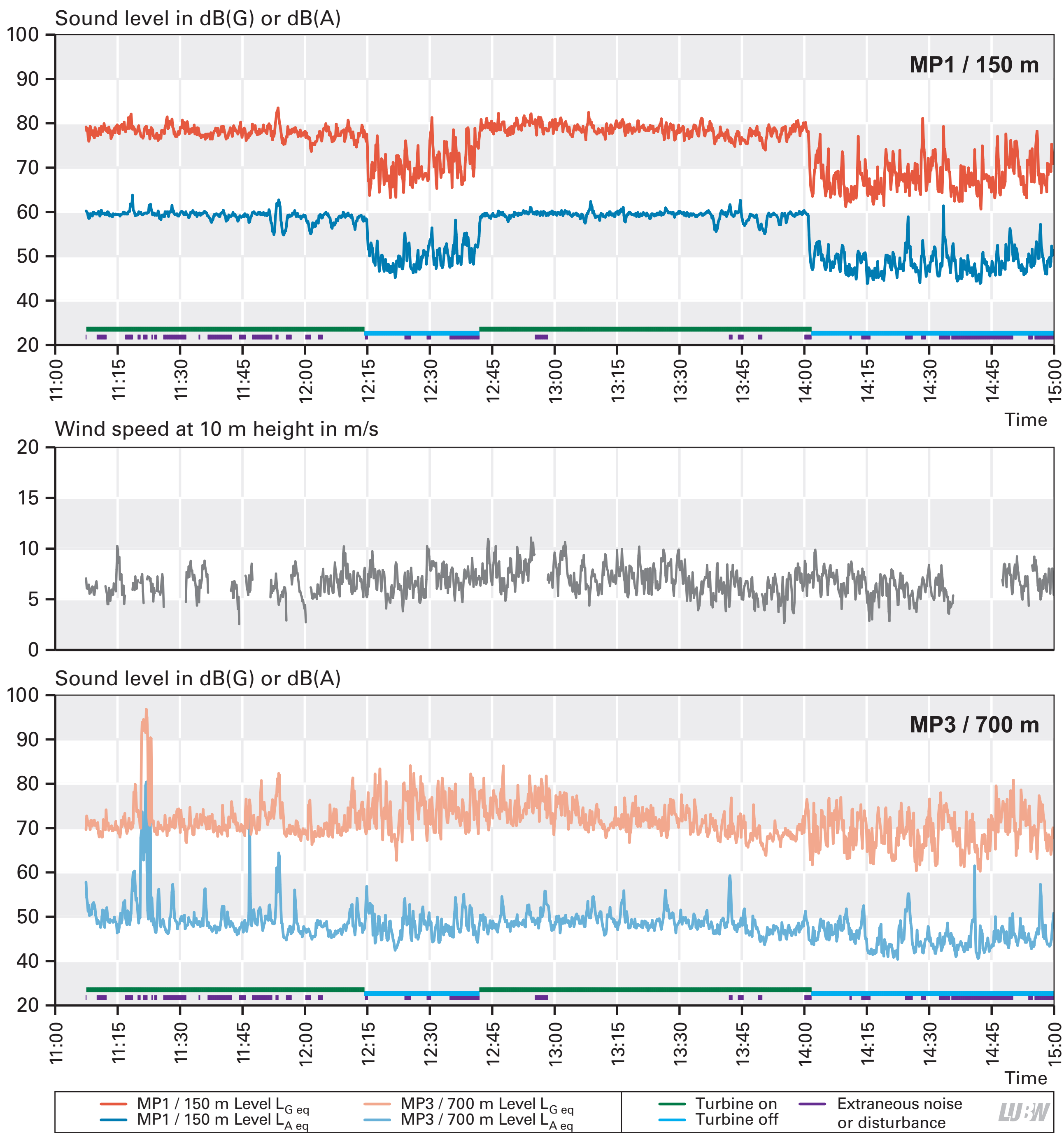


***Figure 4.2-7**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 1*

4.3 Noise at wind turbine 2: Enercon E-66 – 1.8 MW

BASIC CONDITIONS

The wind turbine 2 (WT 2) is a gearless unit by the company Enercon, Model E-66 18/70 (***Figure 4-2***) with a nominal generator capacity of 1.8 MW. The rotor diameter is 70 m, the hub height above ground is 86 m. The immediate vicinity of the turbine consists of agricultural land, with forest partly adjacent to it. Further wind turbines are located in the vicinity. These were completely turned off during the measurement period in order to prevent extraneous noise. A further wind power plant is located at a distance of about 1.5 km; this was in operation during the measurement period. A path in close proximity is allowed to be used only by agricultural traffic and is used very seldom. The measurements were carried out on 02.11.2013 between 10:00 a.m. and 6:00 p.m. The position of the microphone at the measurement point MP1 was at a distance of 120 m from the power plant, measurement point MP2 at a distance of 240 m, both in a downwind direction (in order to take into account the propagation of sound through the wind). The microphone at the measurement point MP3 was positioned at a distance of 300 m from the tower axis and deviated by 30° from the prevailing wind direction. A measurement point at a distance of 700 meters was not possible at this site. ***Figure 4.3-1*** provides an impression.

The measurement was performed in a wind speed range of 5 to 15 m/s (measured at 10 m height), a temperature range of 11 to 12.5 °C, an air pressure range of 926 to 927 hPa and in a power range of 0 to 1,800 kW. The turbulence intensity (see Appendix A3) during the measurement was 28 % and thus relatively high.

RESULTS: NARROW BAND LEVEL

Figure 4.3-2 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 120 m with a resolution of 0.1 Hz. The wind speed was 9 m/s. With the turbine turned on, several discrete maxima can be observed in the infrasound range below 8 Hz. This concerns infrasound generated by the rotor due to its motion. The measured frequencies are in accordance with the passage frequency of a rotor blade and its harmonic overtones. At 22.5 rpm, the speed at which the turbine was running, one can mathematically determine the peaks at 2.2 Hz, 3.4 Hz, 4.5 Hz, 5.6 Hz, 6.8 Hz and 7.9 Hz with good conformance. They disappear when the turbine is turned off; at a distance of 300 m they occur

Figure 4.3-1: *Measurement point MP1 with microphone, reverberant plate and dual wind screen. In the background: wind turbine WT 2 at a distance of 120 m. Photo: Wölfel company.*

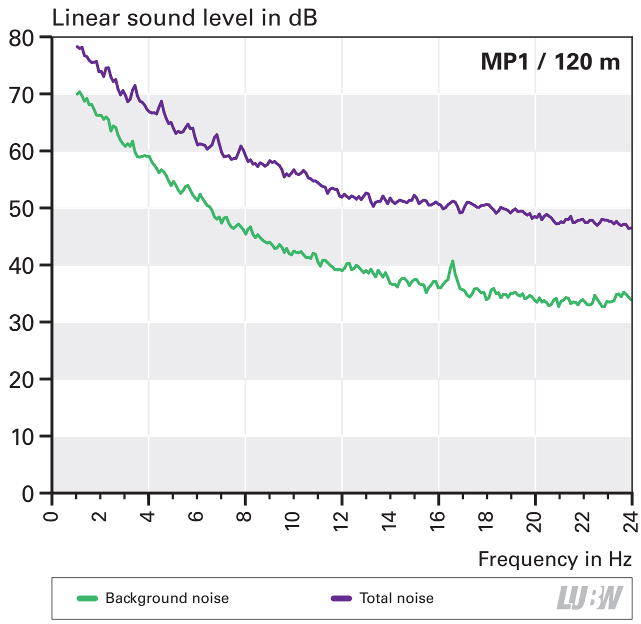


Figure 4.3-2 *Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 2 for the frequency range of infrasound*

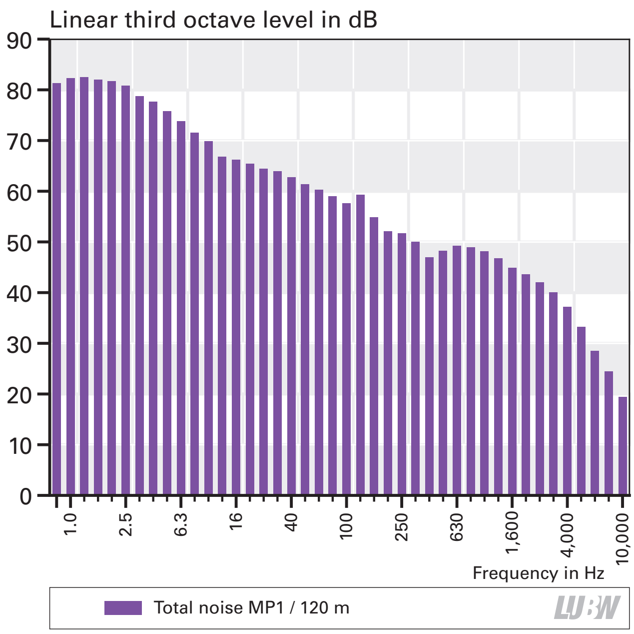


***Figure 4.3-3**: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 2*

only faintly (not shown). The level peak at approx. 17 Hz that is clearly visible in the background is probably due to extraneous noise.

RESULTS: THIRD OCTAVE LEVEL

Figure 4.3-3 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 120 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 9 m/s. The level reduction through switching off the turbine is recognizable in a much broader spectral range here.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.3-4 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP3 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 9 m/s. The background noise of wind and vegetation are also included. These may vary at the respective measurement point. The measurement points MP2 and MP3 are further away from the turbine than measurement point MP1 (240 m and 300 m compared to 120 m). This is where somewhat lower values are also measured, which becomes more apparent with increasing frequency. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were taken and are depicted in ***Figure 4.3-5***. The three charts represent the conditions at distances of 120 m (MP1, upper figure), 240 m (MP2, middle figure) and 300 m with a lateral displacement by 30° to the wind direction (MP3, lower figure). The violet dots in the lower range of values represent audible sound, expressed in dB(A). In the upper image it

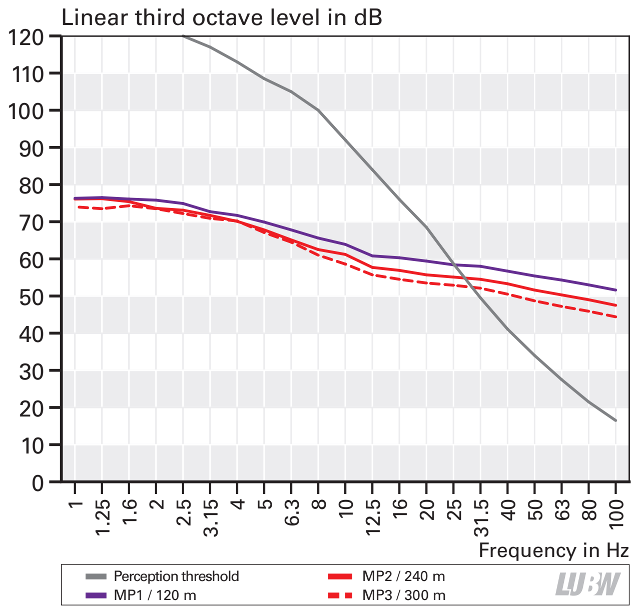


***Figure 4.3-4**: Third octave spectra of total noise at the measurement points MP1 (120 m), MP2 (240 m) and MP3 (300 m) of WT 2, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

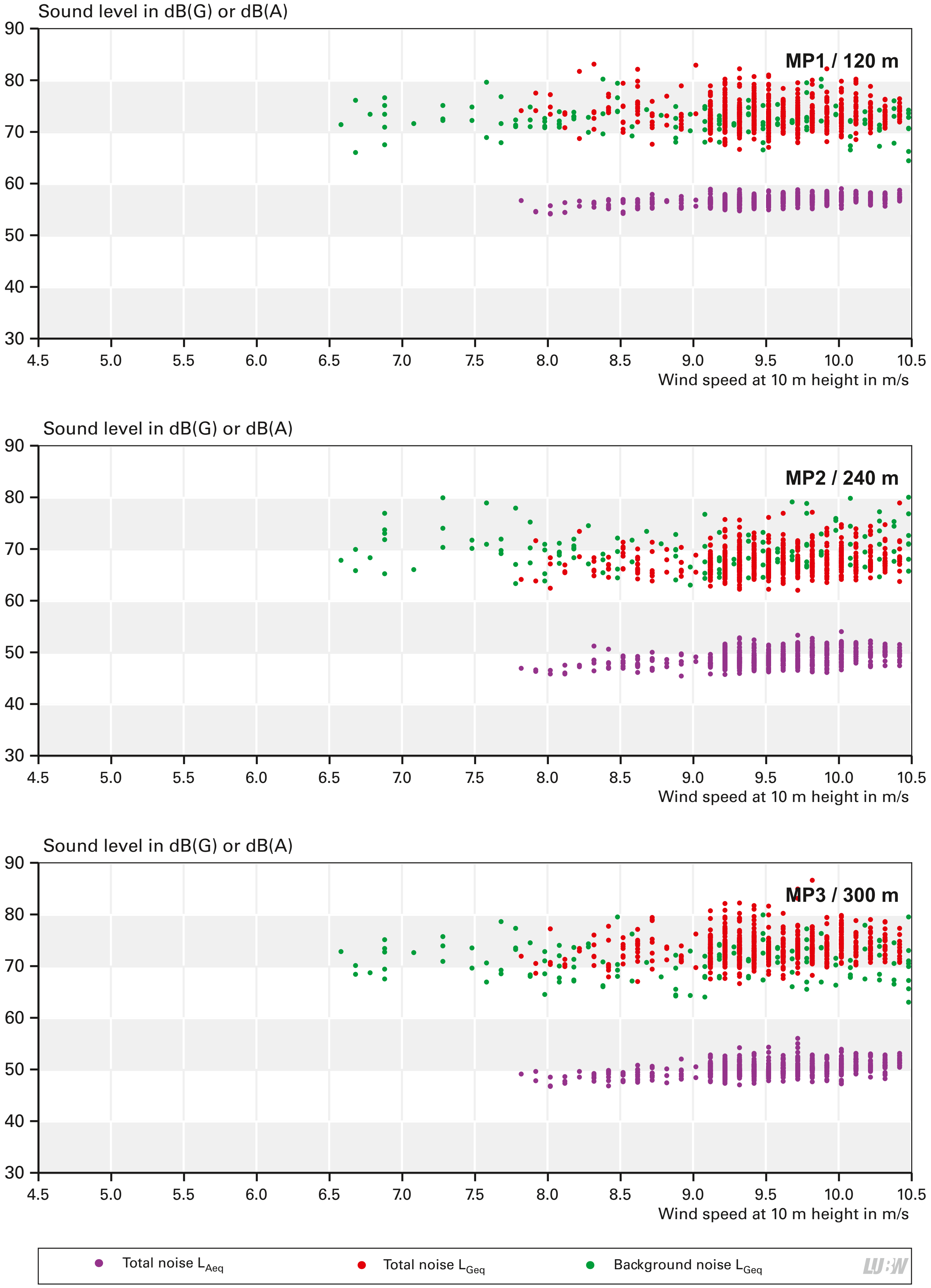


Figure 4.3-5*: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 2. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

can be seen clearly that the measured A levels are higher at a distance of 120 m than at the measurement points at a distance of 240 m and 300 m from the power plant. The turbine was perceived to be louder at a distance of 120 m than at a distance of 240 m.

The red dots represent the G-weighted sound level when the turbine is switched on, the green dots when the turbine is switched off. The upper image shows that at the measurement point MP1, i.e. in the near field at a distance of 120 m from the power plant, the G-weighted sound pressure level during operation of the wind power plant is approximately constant and minimally higher than that of the background noise when the turbine is not running. A similar situation is given at the measurement points MP2 and MP3. Hardly any differences can be seen between the measured values, as the red and green dot clusters pretty-much overlap each other.

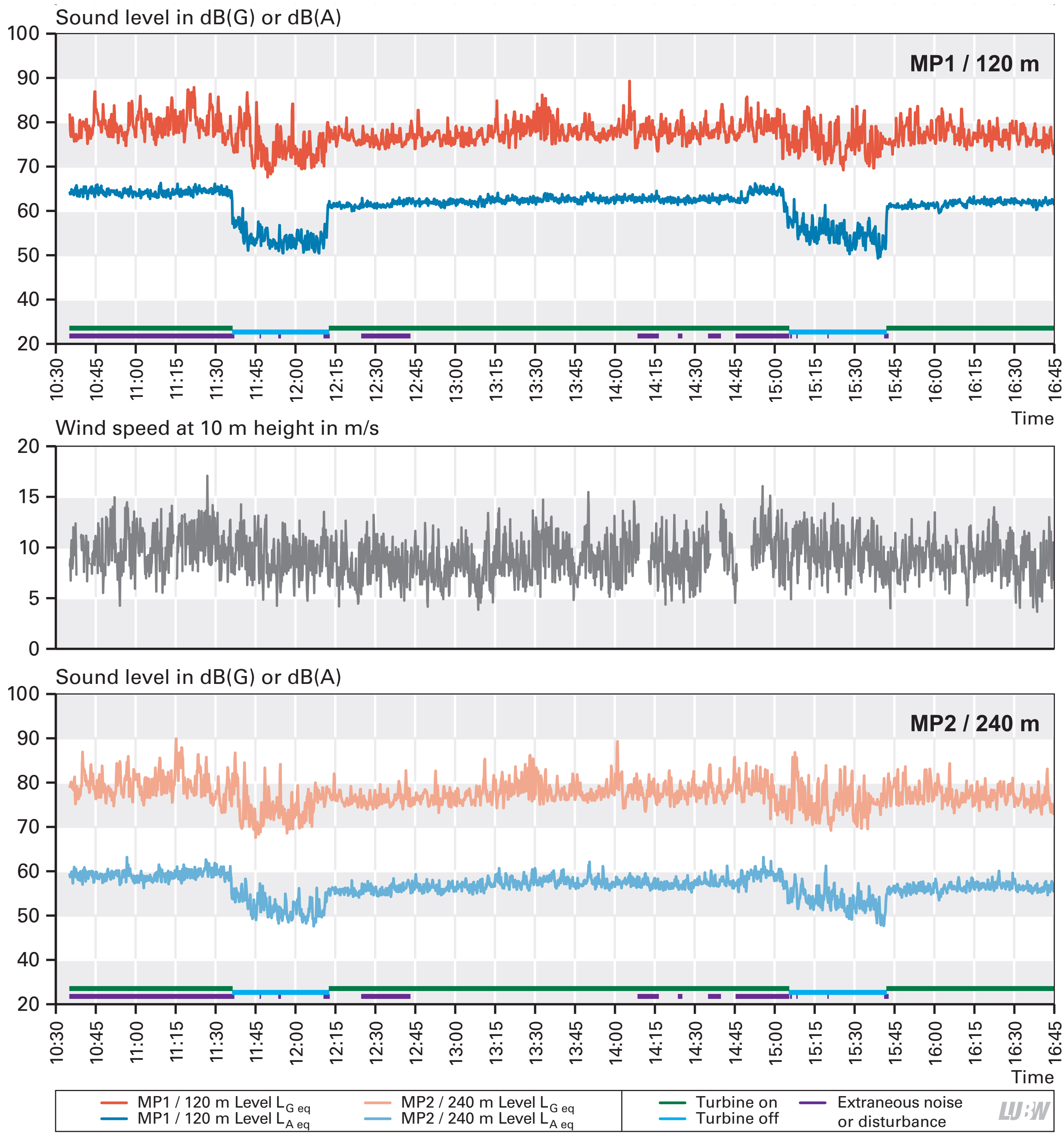


***Figure 4.3-6**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements at the wind turbine WT 2*

The relatively large scattering of the measured values for when the turbine is running and when it is not running, and the relatively high G-weighted sound pressure level – even when the turbine is off – are in this case probably due to the high wind speeds prevailing throughout. The measurements with the turbine in operation were taken in the range of 8 to 11.5 m/s (10 m height). In this case, part of the effect is potentially also attributable to wind-induced noise at the microphones.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.3-6 shows the A and G-weighted level curves between 10:30 a.m. and 5:00 p.m. at a distance of 120 m and 240 m. In addition, the operating conditions of the wind turbine (green = turbine on, light blue = turbine off) as well as periods of time with external noise (violet) are depicted. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. At measurement point MP2, the level drop is less pronounced when the turbine is off, but still clearly recognizable.

Figure 4.4-1*: Wind turbine WT 3 in surroundings used for agricultural purposes. The measurement point with reverberant plate and dual wind screen can be seen in the foreground. Photo: Wölfel company*

4.4 Noise at wind turbine 3: Enercon E-82 – 2.0 MW

BASIC CONDITIONS

The wind turbine 3 (WT 3) is a gearless unit by the company Enercon, Model E-82 E2 (***Figure 4-3***) with a nominal generator capacity of 2.0 MW. The rotor diameter is 82 m, the hub height above ground is 138 m. As can be seen in ***Figure 4.4-1***, agriculturally used areas are located in the closer vicinity. An adjacent wooded area is located at a distance of about 400 meters. A dirt road is located in the immediate vicinity of the power plant, which is used only seldom by agricultural and forestry vehicles. A road is located at a distance of approx. 450 m from the power plant. During the measurement, no traffic noise was noticeable. Further wind turbines from other operators are located at a distance of 1,500 meters. These power plants located further away were in operation during the measurement period. The immissions were not subjectively noticeable during the background noise measurements. The nearest residential building is more than 1,000 meters away. The measurement was carried out on 15.10.2013 between 10:30 a.m. and 3 p.m. The microphone at the measurement point MP1 was located at a distance of 180 meters in a downwind direction from the tower axis, at the measurement point MP2 it was 300 m in a downwind direction. The microphone at the measurement point MP3 was also positioned at a distance of 300 meters, however at an angle of 90° to the downwind direction. A measurement point at a distance of 700 meters was not feasible due to the local conditions.

The measurement was performed in a wind speed range of 2 to 12 m/s (measured at 10 m height), a temperature range of 9 to 13 °C, an air pressure range of 931 to 934 hPa and in a power range of 0 to 2,070 kW. The turbulence intensity (see Appendix A3) during the measurement was 25 % and thus relatively high.

RESULTS: NARROW BAND LEVEL

Figure 4.4-2 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m with a resolution of 0.1 Hz. With the turbine turned on, several discrete maxima can be clearly observed in the infrasound range below 8 Hz. This con-

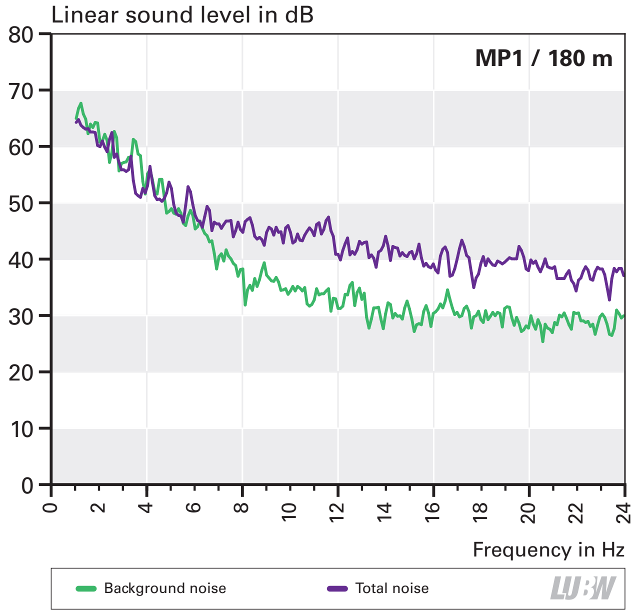


Figure 4.4-2: Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 3 for the frequency range of infrasound

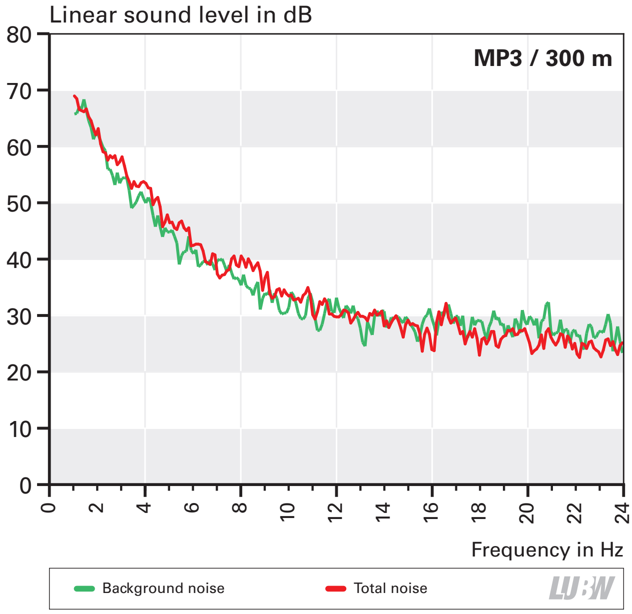


Figure 4.4-3: Narrow band spectra of background noise and total noise in the far range of the wind turbine WT 3 for the frequency range of infrasound

cerns infrasound generated by the rotor due to its motion. The measured frequencies correspond to the passage frequency of a rotor blade (here about 0.83 Hz) and the associated harmonic overtones (2.5 Hz, 3.3 Hz, 4.1 Hz, 5 Hz, 5.8 Hz). The peaks disappear when the power plant is switched off, and occur only slightly at a distance of 300 m (***Figure 4.4-3***). The wind speed was 6 m/s during both measurements.

RESULTS: THIRD OCTAVE LEVEL

Figure 4.4-4 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 6 m/s. Here the level reduction through switching off the turbine is recognizable in a much broader spectral range.

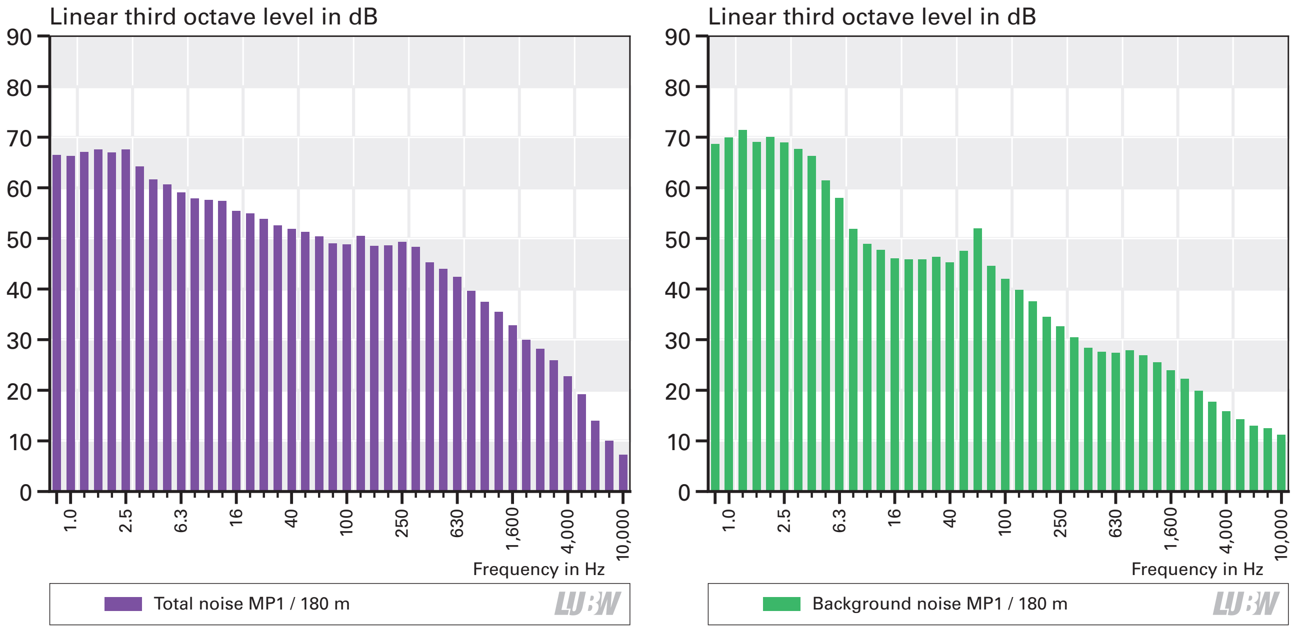


Figure 4.4-4: Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 3

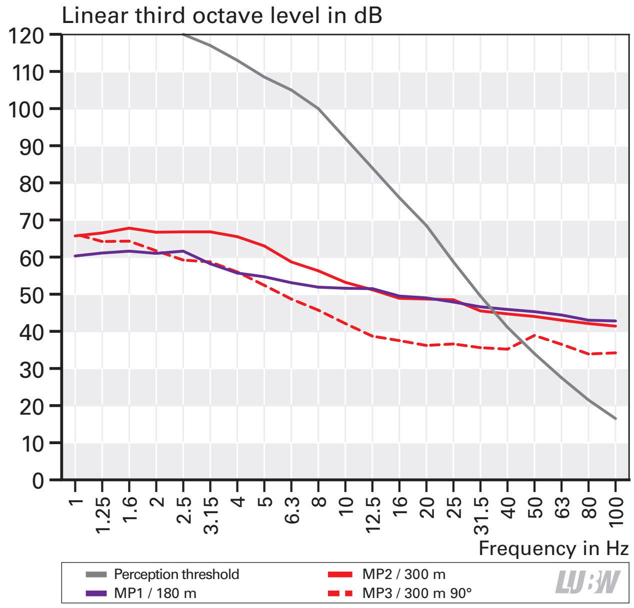


***Figure 4.4-5**: Third octave spectra of the total noise at the measurement points MP1 (180 m), MP2 (300 m) and MP3 (300 m, offset by 90 °) of wind turbine 3, perception threshold according to Table A3-1 for comparison. The measured values were corrected according to Section 4.1.*

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.4-5 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP3 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 9 m/s. It must be kept in mind that the background noise of wind and vegetation are also included. These may vary at the respective measurement point. The measurement points MP2 and MP3 are further away from the power plant than measurement point MP1 (300 m compared to 180 m). Measurement point MP3 is offset to the downwind direction by 90°. Lower values are thus measured there than at measurement point MP2, which is equally far away. The measurement point MP2 is also closer to an existing nearby road than the measurement points MP1 and MP3, which could also be a reason for the slightly higher values. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.4-6***. The three charts represent the relationships at the respective measurement points at the distances 180 m (top), 300 m (centre) and 300 m with lateral offset by 90° to the downwind direction (bottom). Violet dots, which depict the lower curve, represent audible sound, expressed in dB(A). It can be clearly seen that at a distance of 180 m (top image) the measured A levels are higher than at the measurement points at a distance of 300 m from the turbine. The turbine was thus also clearly more perceptible at a distance of 180 m than at a distance of 300 m. The A level first rises with increasingly higher wind speed.

The red dots represent the G-weighted sound level when the wind power plant is switched on, the green dots when the power plant is switched off. Similarly to the A level, it can also be seen for the G level that – despite higher scattering – it increases somewhat with increasing wind speed, and then remains constant.

The top image shows that at MP1, i.e. in the near field at a distance of 180 m from the turbine, the G-weighted sound pressure level during operation of wind turbine 3 is significantly higher than the background noise when the turbine is off. This is far less pronounced at a distance of 300 meters (centre image) and barely detectable at a distance of 300 meters with 90° offset to the downwind direction (bottom image). The red and green dot clusters then overlap each other in many areas.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.4-7 shows the A and G-weighted level development between 10:15 a.m. and 2:45 p.m. for distances of 180 m and 300 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. At measurement point MP2, the recognisable level drop is significantly weaker with the turbine switched off due to the fluctuating background noise.

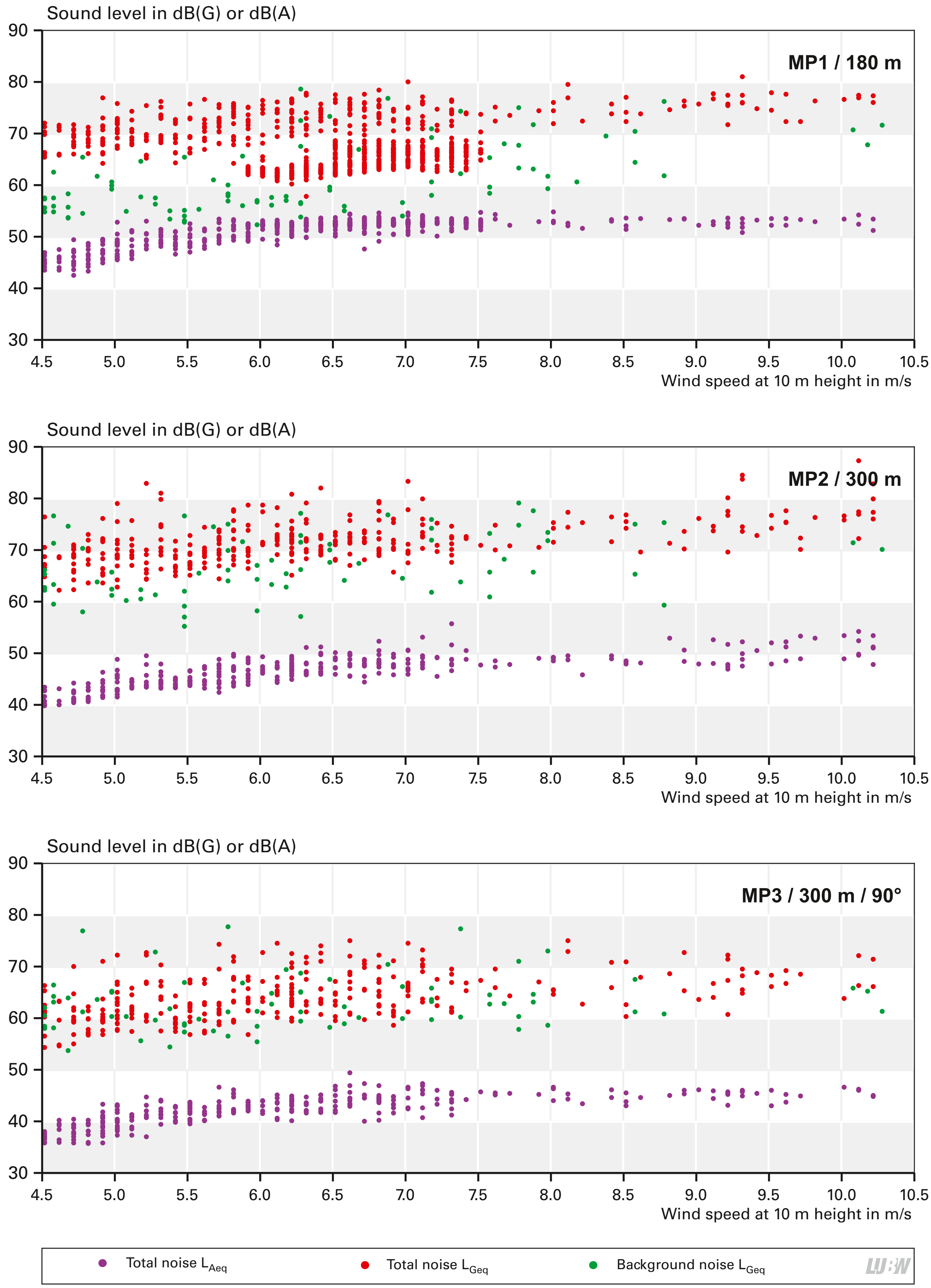


***Figure 4.4-6**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 3. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

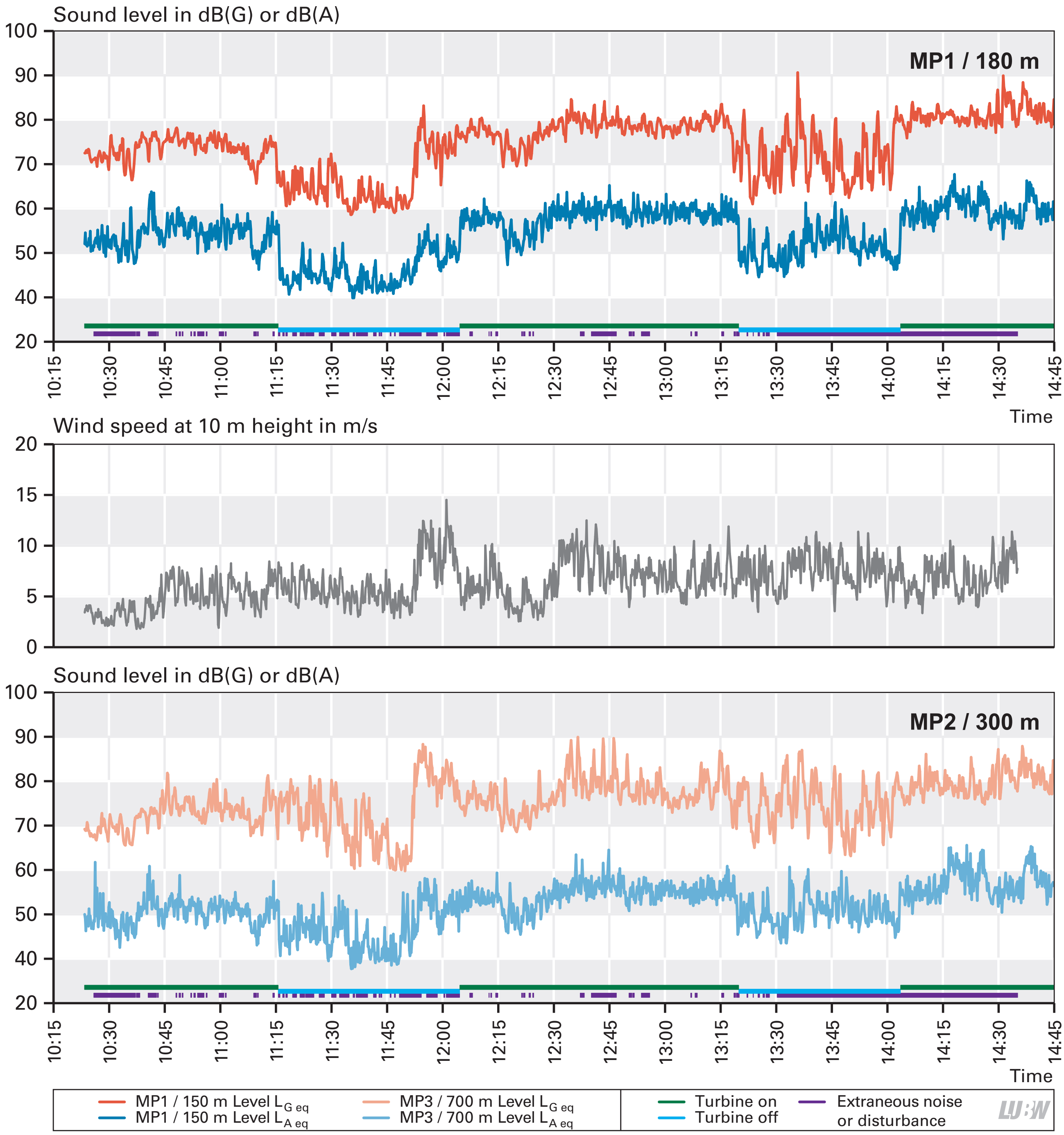


***Figure 4.4-7**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 3*

4.5 Noise at wind turbine 4: REpower 3.2M114 – 3.2 MW

BASIC CONDITIONS

The wind turbine 4 (WT 4) is a unit by the company REpower, type 3.2M114 (***Figure 4-4***) with a nominal generator capacity of 3.2 MW. The rotor diameter is 114 m, the hub height 143 m.

The measured wind turbine is part of a wind farm with several other wind turbines. The adjacent turbines were completely turned off during the measurement period in order to prevent extraneous noise. The vicinity of the turbine consists of agricultural land. A dirt road in the immediate vicinity of the measured turbine is rarely used by agricultural traffic. A forest is located further away. Further wind turbines were in operation at distances of 0.7 km and 2 km, in the opposite direction to the measurement points. Their noise could not be subjectively perceived at any time. The measurements were carried out on 20.03.2014 between 10:00 a.m. and 9:30 p.m. The position of the microphone at the measurement point MP1 was at a distance of 180 m from the turbine, measurement point MP2 and MP3 at a distance of 300 m and measurement point MP4 at a distance of 650 m, in a downwind direction respectively, in order to take into account the most adverse case (promotion of sound propagation through the wind). The measurement point MP2, located directly next to measurement point MP3, served as a comparative measurement point. Its microphone was provided with a primary wind screen and placed into an approx. 50 cm deep hole that was dug especially for that purpose. A secondary wind screen covered the hole flush. The parallel measurements were taken at the measurement points MP2 and MP3 in order to enable a comparison of the measurement values and enable conclusions to be made regarding wind-induced sound components arising at the microphone. The two measurement points MP2 and MP3, as well as the measured turbine, can be seen in ***Figure 4.5-1***. ***Figures 4.5-2 to 4.5-5*** provide an impression of the conditions on site and the measurement technology used.

The measurement was performed in a wind speed range of 3 to 7 m/s (measured at 10 m height), a temperature range

Figure 4.5-1 *(right): Measurement points MP2 and MP3 at a distance of 300 m from the tower axis. Reverberant plate and double wind screen (left), spanned hole in the ground (right). Photo: Wölfel company*

Figure 4.5-2*: View inside the power plant with 143 m hub height. Photo: LUBW*

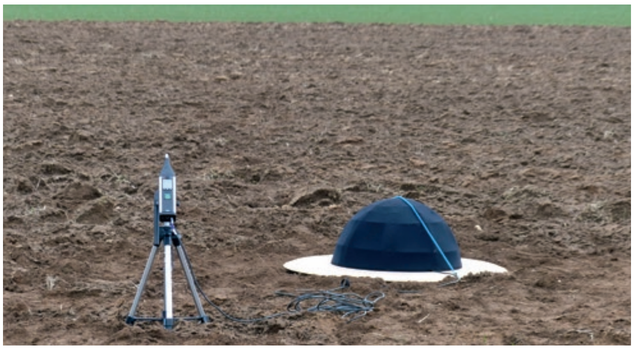


Figure 4.5-3*: Reverberant plate with mounted microphone and dual wind screen. The type DUO measurement device is mounted on a tripod next to it and is connected to the microphone via a measuring cable. Photo: LUBW*

Figure 4.5-4: Anemometer mast for measuring wind speed and wind direction, air pressure, humidity and temperature. The mast is extended to 10 m (not yet extended in the image). Photo: LUBW

Figure 4.5-5: Data is constantly collected inside the system during the measurement and transmitted by radio (left). Photo: LUBW

of 15 to 19 °C, an air pressure range of 979 to 981 hPa and in a power range of 0 to 3,170 kW. The turbulence intensity (see Appendix A3) during the measurement was 15 %.

RESULTS: NARROW BAND LEVEL

Figure 4.5-6 shows the narrow band spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m with a resolution of 0.1 Hz. With the turbine turned on, clearly visible maxima can be seen in the infrasound range. The measured frequencies correspond to the passage frequency of a rotor blade (here approximately 0.6 Hz) and its harmonic overtones at 1.2 Hz, 1.8 Hz, 2.4 Hz, 3 Hz, etc. This concerns infrasound generated by the rotor due to its motion. The peaks disappear when the turbine is switched off. ***Figure 4.5-7*** shows the narrowband spectra of background noise and total noise at the measurement point MP4 at a distance of 650 m. At this location the discrete infrasound maxima (see measurement point MP1) are still detectable with the wind power plant turned on. The recognizable slightly higher levels at measurement point MP4, with frequencies lower than 5 Hz, cannot be attributed to turbine operation. The cause for

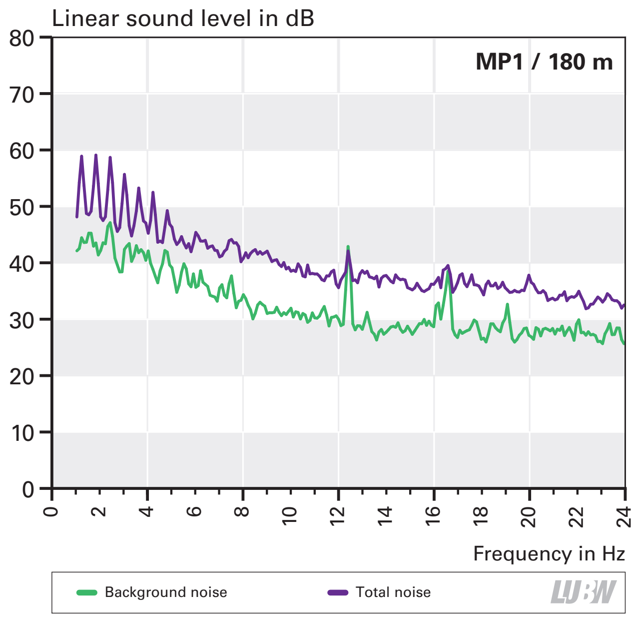


Figure 4.5-6: Narrow band spectra of background noise and total noise in the vicinity of the wind turbine WT 4 for the frequency range of infrasound

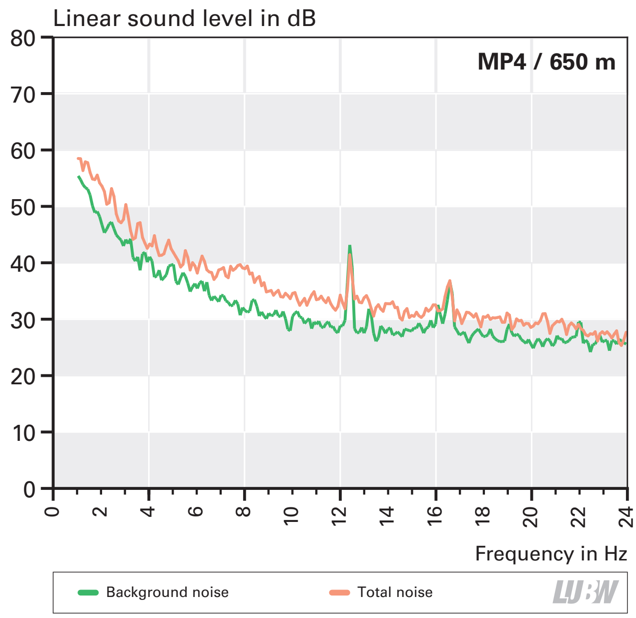


Figure 4.5-7: Narrow band spectra of background noise and total noise in the far range of the wind turbine WT 4 for the frequency range of infrasound

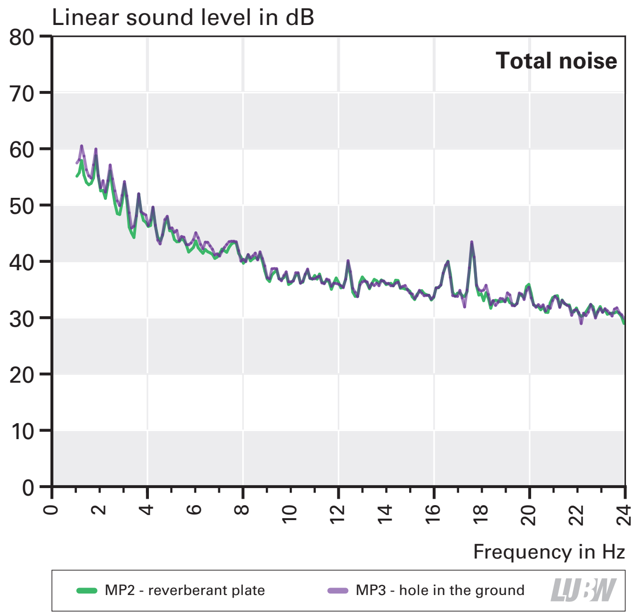


Figure 4.5-8: *Narrowband spectra of the total noise at the measurement points MP2 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 4 for the range of infrasound. The distance from the turbine was 300 m*

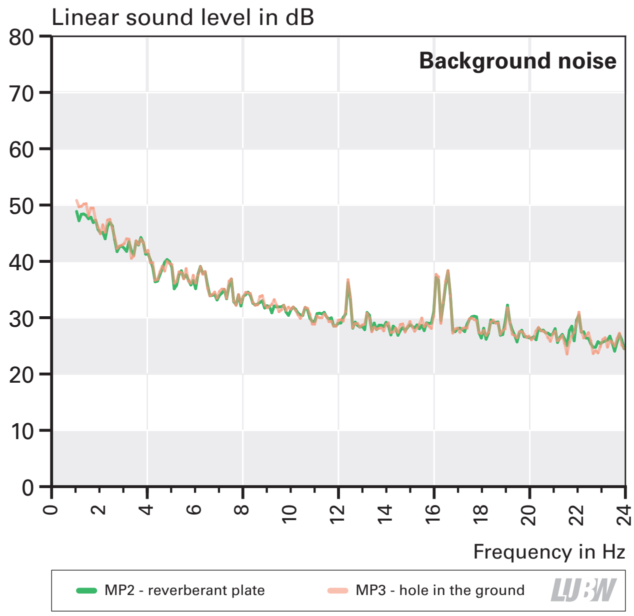
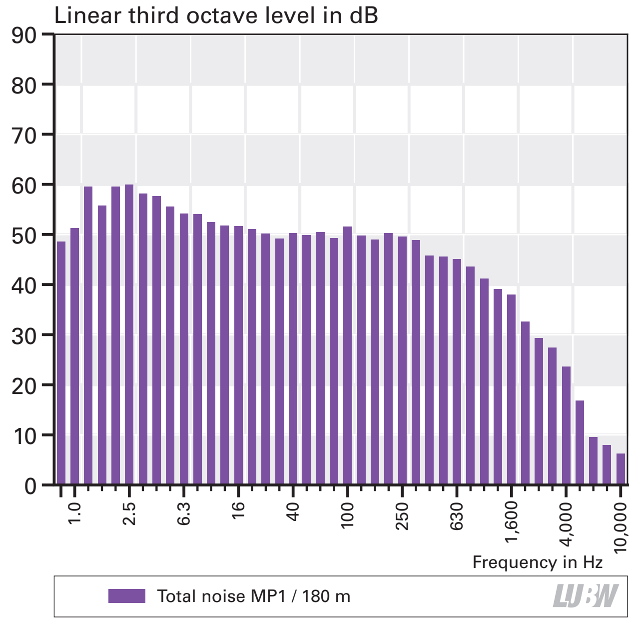


Figure 4.5-9: *Narrowband spectra of the background noise at the measurement points MP2 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 4 for the range of infrasound. The distance from the turbine was 300 m.*

the up to 10 dB higher values is another background noise at the measurement point MP4 compared to the measurement point MP1. The wind speed was 5.5 m/s for both measurements.

The comparison of narrowband spectra for the two measurement points MP2 and MP3 in ***Figures 4.5-8 to 4.5-9*** shows that there is no significant difference between the two measurement points for the range of infrasound. The wind speed was 5.5 m/s respectively. It can therefore be assumed that below 20 Hz neither the absorption of the secondary wind screen nor the ground influences play a role. The increase in level towards lower frequencies was present in this measurement to an equal extent both with and without a hole in the ground. The expected reduction in the wind-induced background noise in the infrasound range cannot be observed in a direct comparison between the two measurement points. Further investigations regarding the issue of noise at the microphone induced by the wind were thus not deemed necessary.



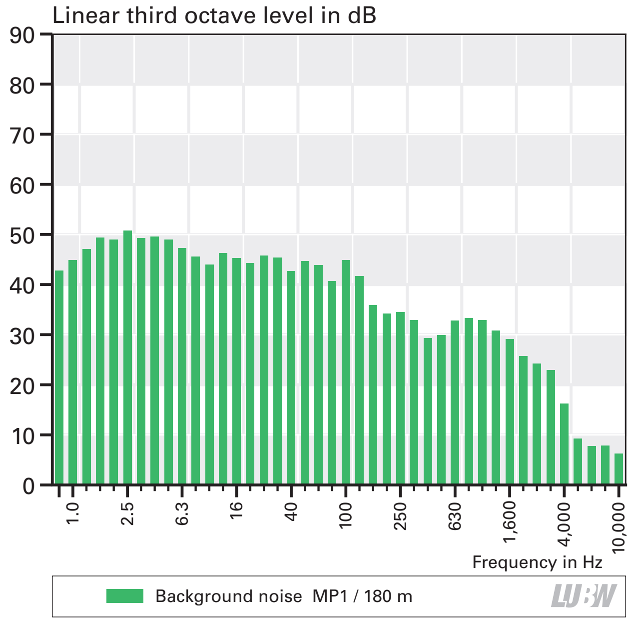


Figure 4.5-10: *Third octave spectra of total noise and background noise in the vicinity of the wind turbine WT 4*

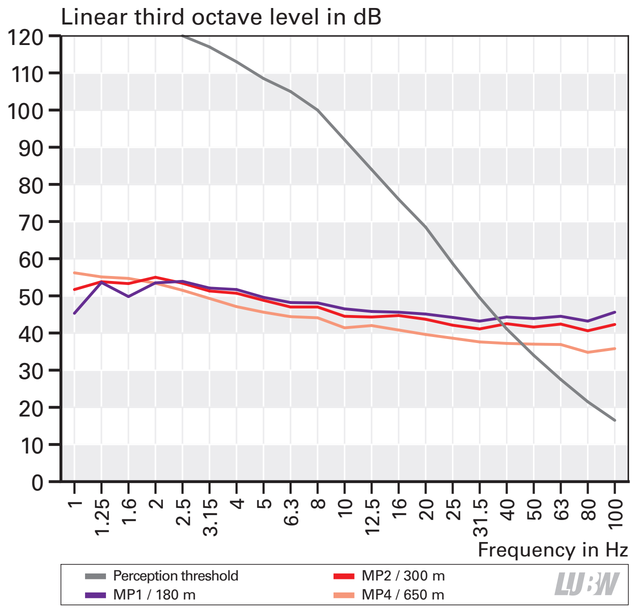


Figure 4.5-11*: Third octave spectra of total noise at the measurement points MP1 (180 m), MP2 (300 m) and MP4 (650 m) of WT 4, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

Figure 4.5-10 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 180 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 5.5 m/s. Here the level reduction through switching off the turbine is recognizable in a much broader spectral range.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.5-11 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP4 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 5.5 m/s. It must be kept in mind that the background noise of wind and vegetation are also included. These may vary at the respective measurement point. The measurement points MP2 and MP4 are further away from the turbine than MP1 (300 m and 650 m compared to 180 m). This is where somewhat lower values are also measured, which becomes more apparent with increasing frequency. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.5-12***. The three charts represent the relationships at the respective measurement points at the distances 180 m (top), 300 m (centre) and 650 m (bottom). Violet dots, which depict the lower value area, represent audible sound, expressed in dB(A). It can be seen clearly that the measured A levels are higher at a distance of 180 m (upper image) than at the measurement points at a distance of 300 m and 650 m from the turbine.

The red dots represent the G-weighted sound level when the wind turbine is switched on, the green dots when the turbine is switched off. The data shows that the G-weighted sound pressure level of the tested measurement points increases slightly during operation of the wind turbine with increasing wind speed. For the G-weighted sound pressure level of the background noise, no connection can be ascertained with the wind speed for the main part of the measuring period. However, the readings are also in a similar order with the turbine switched off due to strongly fluctuating wind conditions (gusts, turbulence). Lower levels were observed for the background noise merely for a late, roughly 30-minute measurement period from 8:50 p.m. onwards. During this period, the mean normalized wind speed was relatively constant at 5.5 m/s.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.5-13 shows the A and G-weighted level development between 4:00 p.m. and 9.00 p.m. for the distances of 180 m and 650 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. A level drop is also evident with the turbine switched off at measurement point MP3.

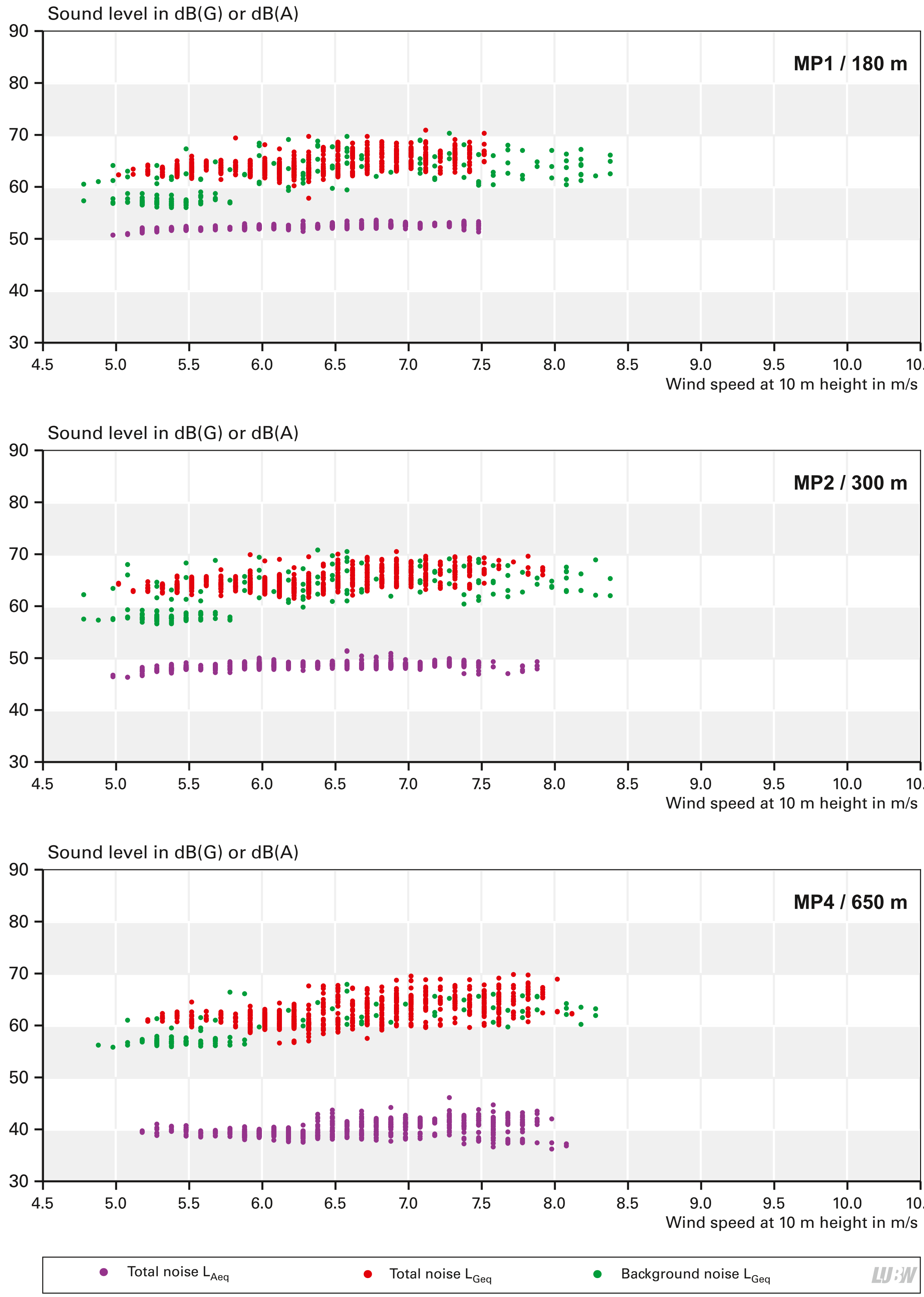


Figure 4.5-12*: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 4. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

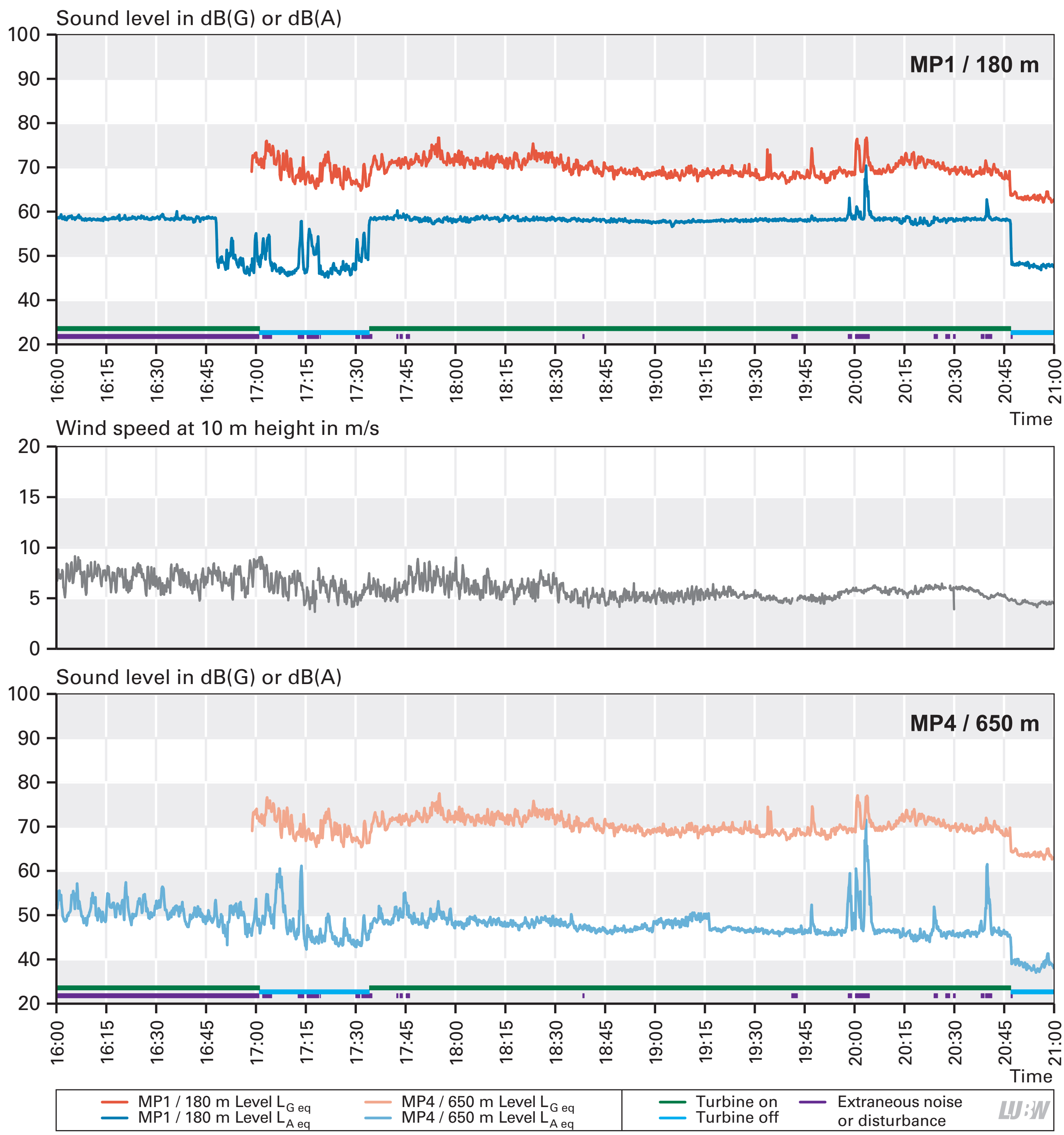


Figure 4.5-13*: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements at wind turbine WT 4*

4.6 Noise at wind turbine 5: Nordex N117 – 2.4 MW

BASIC CONDITIONS

The wind turbine 5 (WT 5) is a unit by the company Nordex, type N117/2400, with a nominal generator capacity of 2.4 MW (***Figure 4-3 and 4.6-1***). The rotor diameter is 117 m, the hub height above ground is 140.6 m.

The measured turbine is part of a wind farm with several wind turbines. The adjacent turbines were completely turned off during the measurement period in order to prevent extraneous noise. The vicinity of the turbine consists of agricultural land. A dirt road is located in the immediate vicinity of the turbine, which is used only very seldom by agricultural and forestry vehicles. A district road is located about 400 meters south of the investigated wind power plant, and another road roughly 1,000 m east. During the measurement, no traffic noise was subjectively perceptible. A forest is located further away. The measurements were carried out on 13.01.2015 between 11:00 a.m. and 4:00 p.m. The microphone position of the measurement point MP1 was 185 meters from the turbine, the measurement point MP2 300 m and the measurement points MP3 and MP4 each 650 m from the turbine. All measurement points were located in a downwind direction in order to take into account a generally unfavourable situation (promotion of sound propagation through the wind). The measurement points MP3 and MP4 were immediately next to one another and served as a comparison. The microphone MP3 was provided with a primary wind screen and placed into an approx. 50 cm deep hole that was dug especially for that purpose. A secondary wind screen covered the hole flush. The parallel measurements were taken at the measurement points MP3 and MP4 in order to enable a comparison of the levels and allow conclusions to be made regarding wind-induced sound components arising at the microphone.

Figure 4.6-1*: Wind turbine WT 5 in surroundings used for agricultural purposes. In the foreground you can see the 10 m high wind measurement mast. Photo: Wölfel company*

The measurement was performed in a wind speed range of 5 to 12 m/s (measured at 10 m height), a temperature range of 10 to 13 °C, an air pressure range of 975 to 979 hPa and in a power range of 0 to 2,400 kW. The turbulence intensity (see Appendix A3) during the measurement was 13 %.

RESULTS: NARROW BAND LEVEL

Figures 4.6-2 to 4.6-5 show narrow band spectra of background noise and total noise for different measurement locations with a resolution of 0.1 Hz. The wind speed was 7.6 m/s during the measurement of the total noise and 6.9 m/s during the measurement of the background noise.

Figure 4.6-2 shows the results of measurement point MP1 at a distance of 185 m. With the turbine turned on, several discrete maxima can be seen in the infrasound range below 6 Hz. This concerns infrasound generated by the rotor due to its motion. The measured frequencies correspond to the passage frequency of a rotor blade of about 0.6 Hz and its harmonized overtones at 1.2 Hz, 1.7 Hz, 2.3 Hz, 2.9 Hz, 3.5 Hz, 3.9 Hz, etc. The peaks disappear when the turbine is switched off.

Figure 4.6-3 shows the narrow band spectra of background noise and overall noise at the measurement point MP4 at a distance of 650 m. At this distance, the infrasound maxima

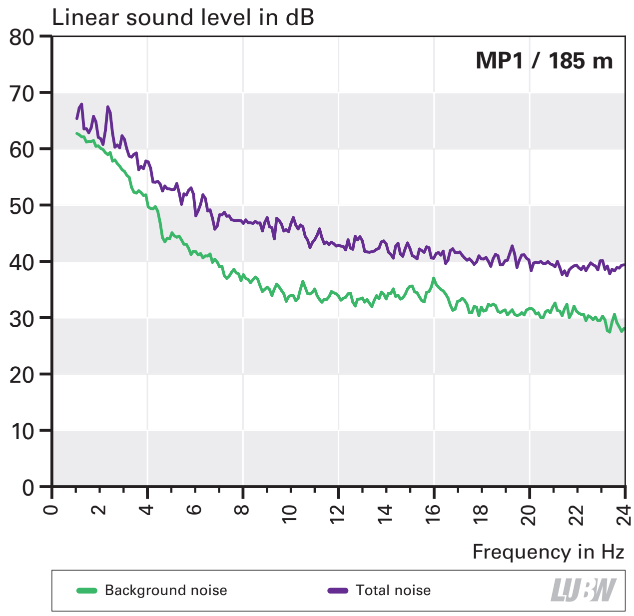


Figure 4.6-2: Narrow band spectra of background noise and total noise in the vicinity of wind turbine WT 5 for the frequency range of infrasound

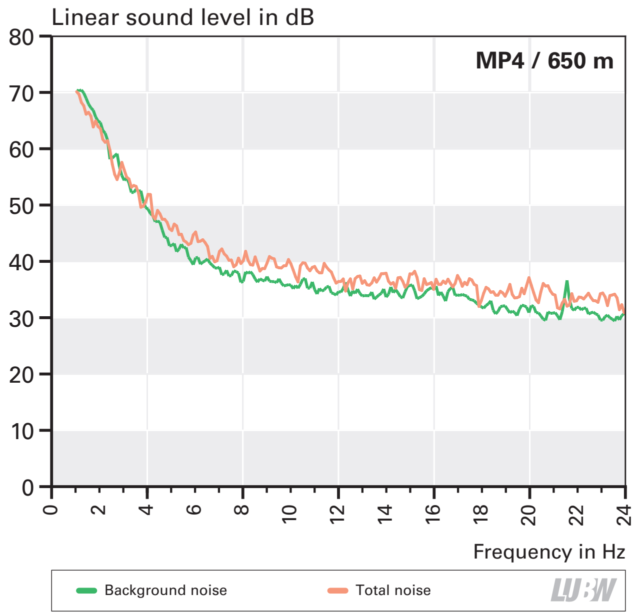


Figure 4.6-3: Narrow band spectra of background noise and total noise in the far range of wind turbine WT 5 for the frequency range of infrasound

of measurement point MP1 with the wind turbine switched on can no longer be distinguished. Between the states "turbine on" and "turbine off" there were only minor differences in infrasound for this measurement at a distance of 650 m. The infrasound here was primarily due to the sounds of wind and from the surroundings. The comparison of the narrowband spectra for the two measurement points MP3 (hole in the ground) and MP4 (reverberant plate) at a distance of 650 meters in ***Figures 4.6-4 to 4.6-5*** illustrates that in the infrasound range there is generally no significant difference between the two measurement points. Only at frequencies between 2 Hz and 8 Hz did the measurements in the hole in the ground show slightly higher levels. Neither the absorption of the secondary wind screen nor the ground influence appear to be of significance below 20 Hz. The increase in level towards lower

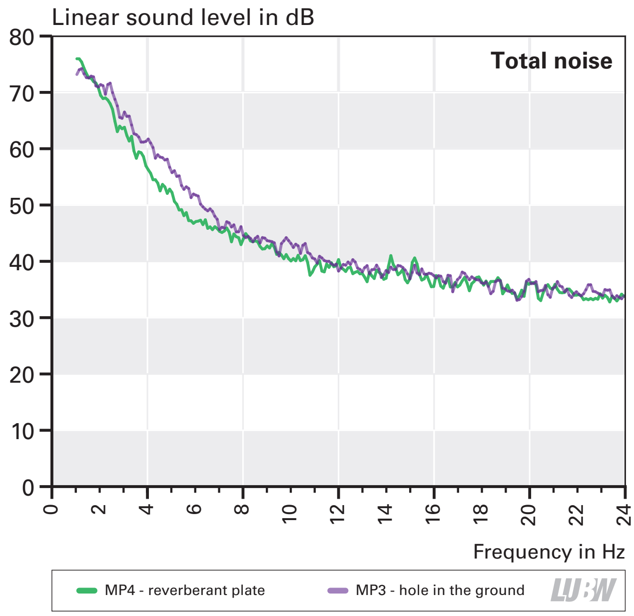


Figure 4.6-4: Narrowband spectra of the total noise at the measurement points MP4 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 5 for the range of infrasound. The distance from the turbine was 650 m.

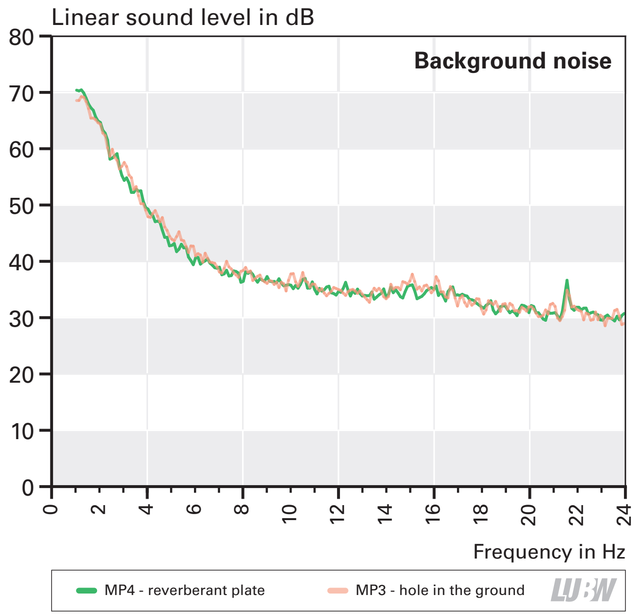


Figure 4.6-5: Narrowband spectra of the background noise at the measurement points MP4 (reverberant plate) and MP3 (hole in the ground) of the wind turbine WT 5 for the range of infrasound. The distance from the turbine was 650 m.

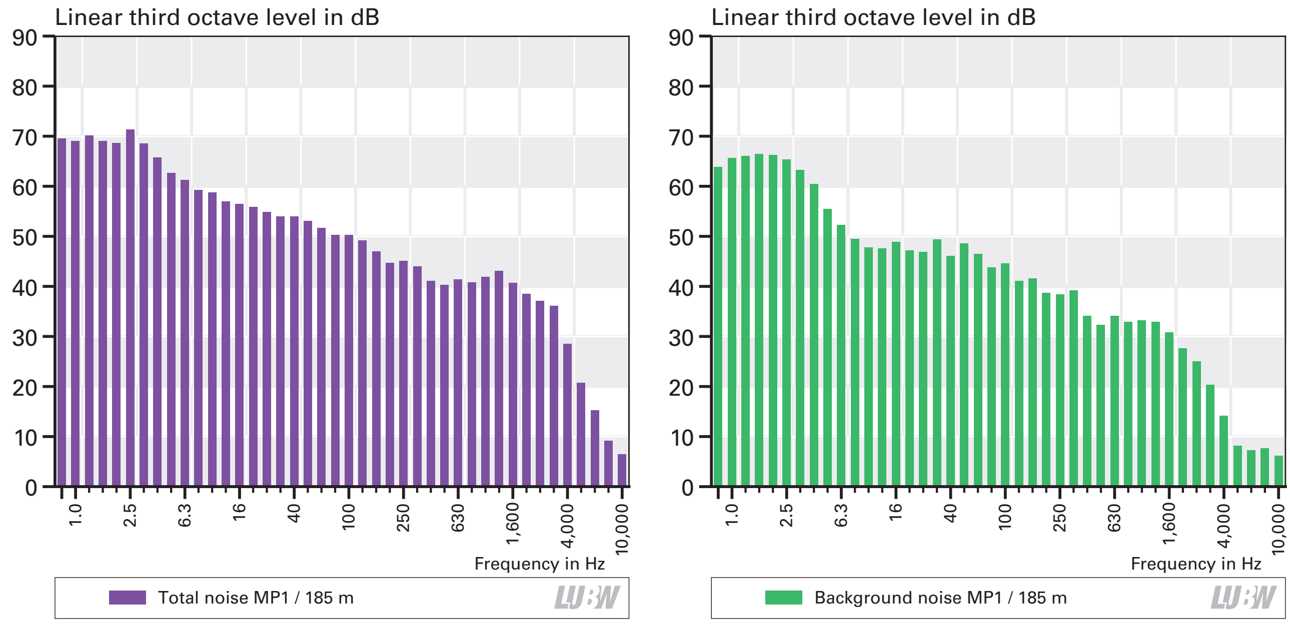


Figure 4.6-6*: Third octave spectra of total noise and background noise in the vicinity of wind turbine WT 5*

frequencies was present during this measurement with and without the hole in the ground. The expected reduction in the wind-induced background noise in the infrasound range cannot be observed in a direct comparison between the two measurement points (see also Section 4.5).

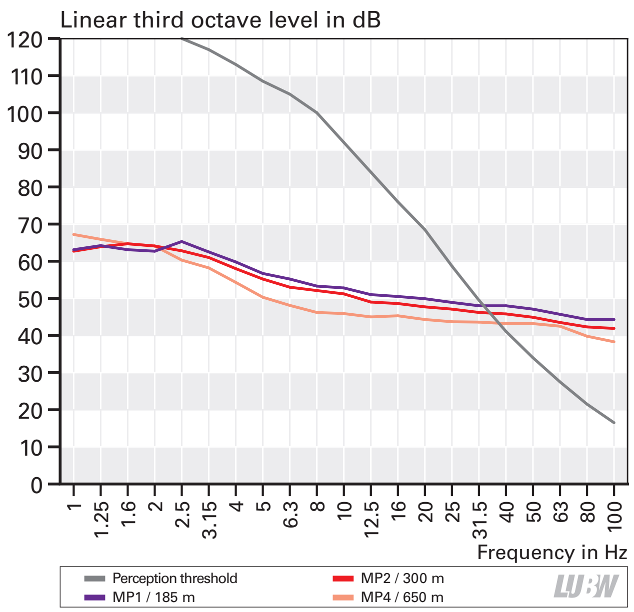


Figure 4.6-7*: Third octave spectra of total noise at the measurement points MP1 (185 m), MP2 (300 m) and MP4 (650 m) of WT 5, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

Figure 4.6-6 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 185 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 5.5 m/s. The influence of the turbine in a much broader spectral range can be recognised here.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.6-7 shows the third octave spectra of the total noise at the measurement points MP1, MP2 and MP4 for the frequency range from 1 Hz to 100 Hz along with the perception threshold in comparison. The wind speed was 7 m/s. It must be kept in mind that the background noise (wind, vegetation) is also included. This may vary at the respective measurement points. The measurement points MP2 and MP4 were further away from the turbine than measurement point MP1 (300 m and 650 m compared to 185 m). As expected, somewhat lower values were measured there, which becomes more apparent with increasing frequency. In the range of infrasound, the curves are well below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.6-8***. The three

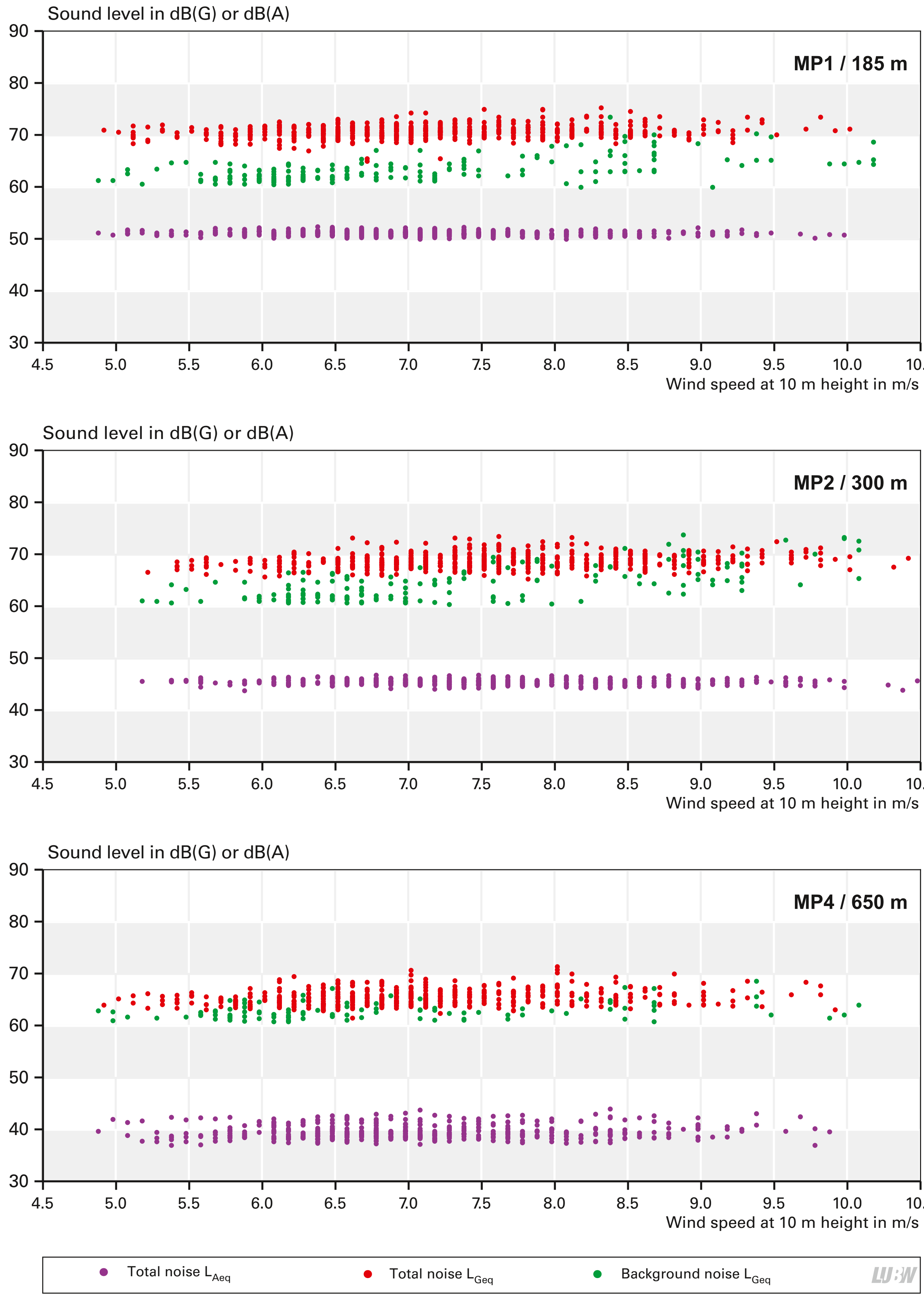


***Figure 4.6-8**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 5. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

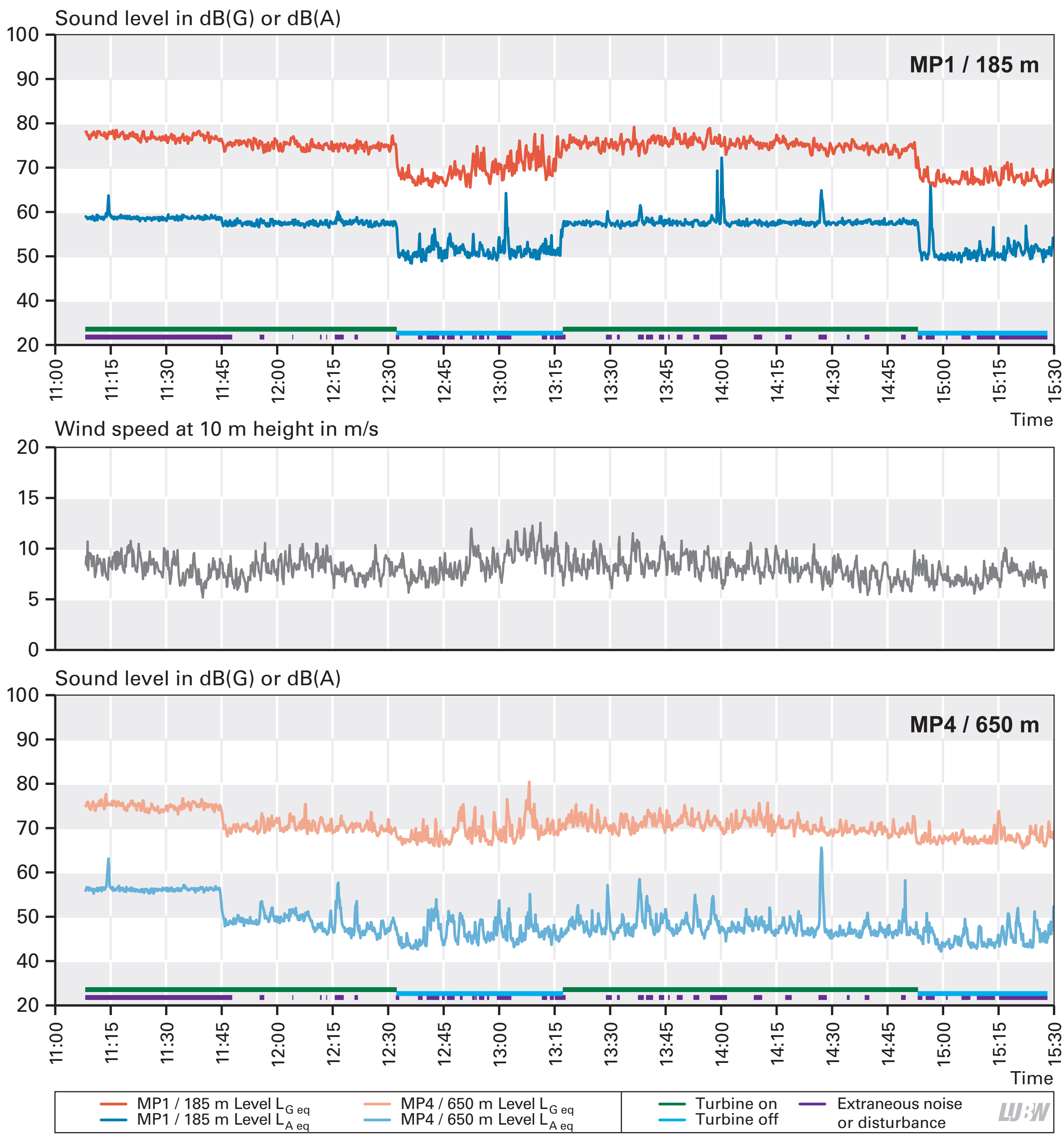


***Figure 4.6-9**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 5*

charts represent the relationships at the measurement points MP1 (185 m), MP2 (300 m) and MP4 (650 m).

The violet dots represent audible sound, expressed in dB(A). It is clearly visible that the measured A levels are higher close to the turbine than at the measurement points that are further away. The red dots represent the G-weighted sound level when the turbine is switched on, the green dots when the turbine is switched off. The figure shows that the G-weighted sound pressure levels at the measurement points examined during operation and standstill of the WT have no significant connection with the increase in wind speed. This fairly constant level curve can also be seen in the A-weighted level development. At measurement point MP1, a significantly increased mean G level can be seen during operation of the wind turbine compared to turbine standstill. As expected, the level difference between the states "turbine on" and "turbine off" decreases

Figure 4.7-1: Wind turbine WT 6 in surroundings used for agricultural purposes. The measurement point MP1 with reverberant plate and dual wind screen can be seen in the foreground. Photo: Wölfel company

with increasing distance. The A level also drops from values greater than 50 dB(A) at measurement point MP1 to values of around 40 dB(A) at measurement point MP4.

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.6-9 shows the A and G-weighted level developments between 11:00 a.m. and 5:30 p.m. for distances of 185 m and 650 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is recognisable through the considerably declining level developments. At measurement point MP4, a level drop with the turbine switched off due to the fluctuating background noise is only slightly recognisable.

4.7 Noise at wind turbine 6: Enercon E-101 – 3.05 MW

BASIC CONDITIONS

The wind turbine 6 (WT 6) is a unit by the company Enercon, type E-101 (***Figure 4-6***) with a nominal generator capacity of 3.05 MW. The rotor diameter is 101 m, the hub height above ground is 135.4 m.

The measured turbine is part of a wind farm with several wind turbines. The adjacent turbines were completely turned off during the measurement period in order to prevent extraneous noise. The nearest other turbine that was in operation during the measurement period was located at a distance of approx. 850 m and was subjectively not perceptible over the entire measuring period. The vicinity of the turbine consists primarily of agricultural land. A dirt road is located in the immediate vicinity of the turbine, which is used only very seldom by agricultural and forestry vehicles. A state road is located at a distance of approx. 480 m eastward of the examined wind power plant. During the measurement, only occasionally traffic noise was perceptible. The measurements were carried out on 15.01.2015 between 12:00 p.m. and 3:00 p.m. The position of the microphone at the measurement point MP1 was located at a distance of 192 m from the turbine; the measurement point MP2 at a distance of 305 m and the measurement point MP3 at a distance of 705 m. The measurement points were each in a downwind direction in order to take into account the generally most unfavourable situation (promotion of sound propagation through the wind). The measurement point MP1 and the measured turbine can be seen in ***Figure 4.7-1***.

The measurement was performed in a wind speed range of 2.8 mm/s to 9.9 m/s (measured at 10 m height), a temperature range of 6 °C to 7 °C, an air pressure range of 954 hPa to 956 hPa and in a power range of 0 to 3,050 kW. The turbulence intensity (see Appendix A3) during the measurement was 14 %.

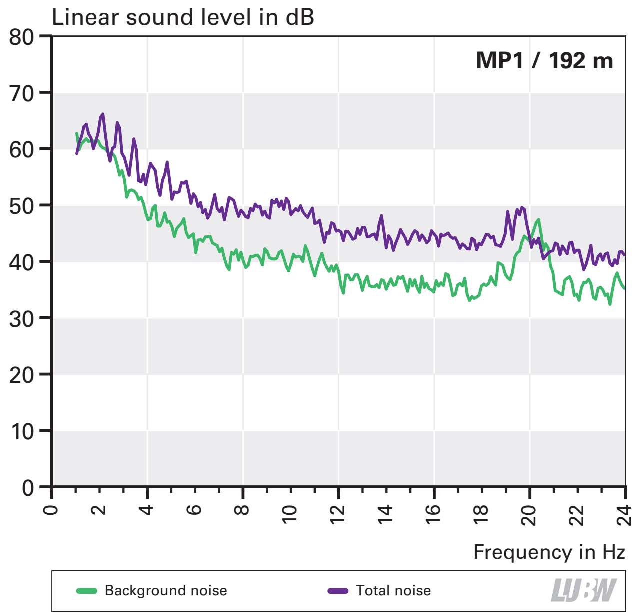


Figure 4.7-2*: Narrow band spectra of background noise and total noise in the vicinity of wind turbine WT 6 for the frequency range of infrasound*

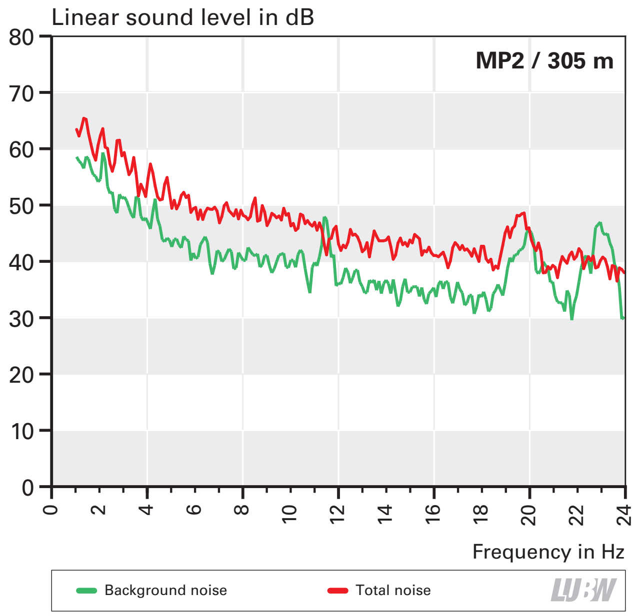


Figure 4.7-3*: Narrow band spectra of background noise and total noise in the far range of wind turbine WT 6 for the frequency range of infrasound*

RESULTS: NARROW BAND LEVEL

Figures 4.7-2 to 4.7-3 show the established narrow band spectra for the operation of WT 6 with a mean wind speed of approximately 5.6 m/s at a height of 10 m. Clearly visible maxima can be seen at the measurement points MP1 and MP2. The measured frequencies correspond to the passage frequency of a rotor blade (here approx. 0.7 Hz) and the harmonic overtones at 1.4 Hz, 2.1 Hz und 2.8 Hz. This concerns infrasound generated by the rotor due to its motion. The peaks disappear when the turbine is switched off. At the measurement point MP3 at a distance of 705 m (not pictured), the mentioned maxima no longer occur so clearly. The level maximum at approx. 20 Hz is striking, which is clearly visible at all measurement points. However, it is highly likely that this is not attributable to the wind turbine, as it is also evident in the background noise.

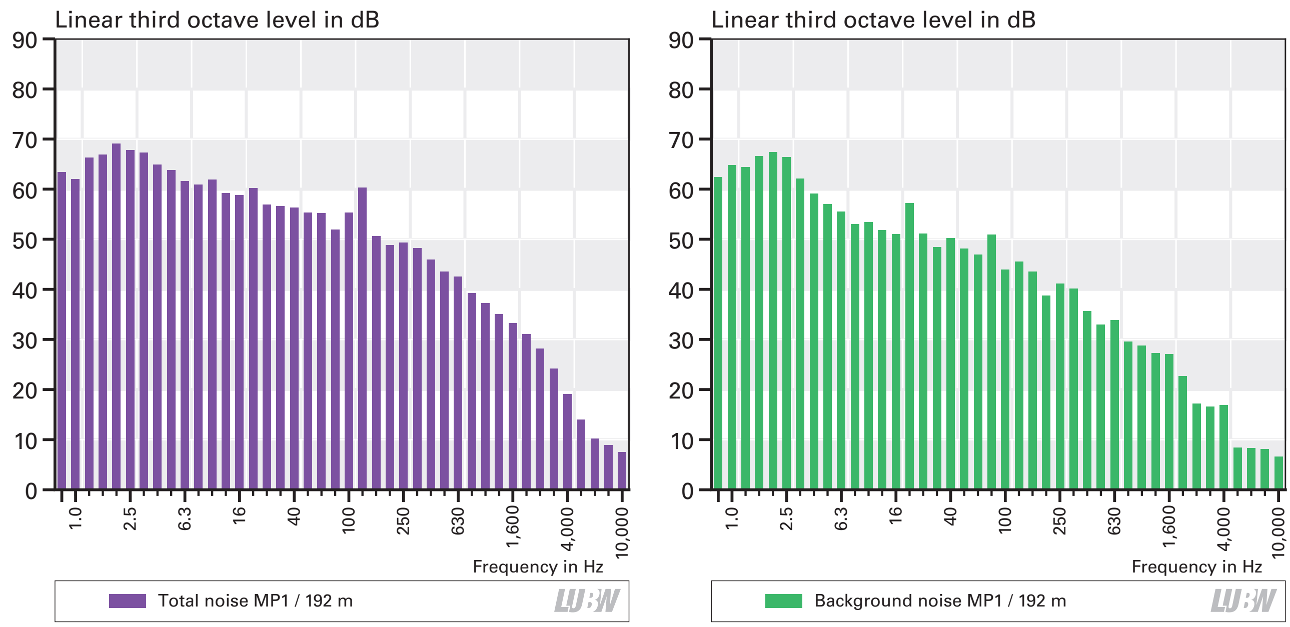


Figure 4.7-4*: Third octave spectra of total noise and background noise in the vicinity of wind turbine WT 6*

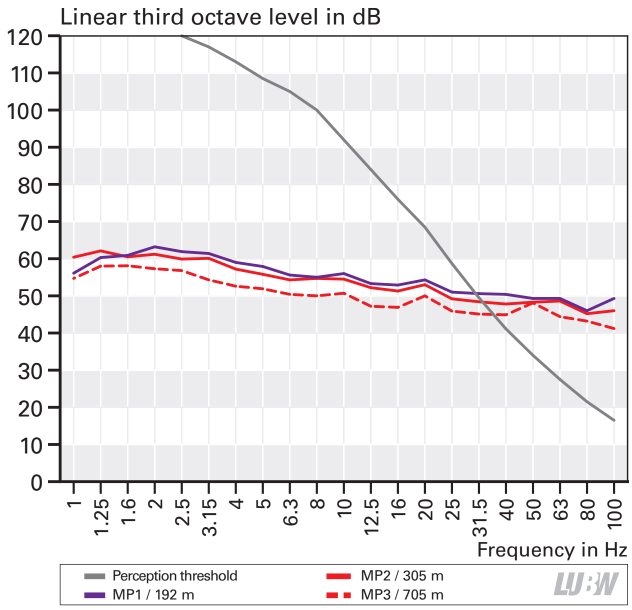


***Figure 4.7-5**: Third octave spectra of total noise at the measurement points MP1 (192 m), MP2 (305 m) and MP3 (705 m) of WT 6, with the perception threshold according to Table A3-1 in comparison. The measured values were corrected according to Section 4.1.*

RESULTS: THIRD OCTAVE LEVEL

Figure 4.7-4 shows the third octave spectra of background noise and overall noise at the measurement point MP1 at a distance of 192 m for the frequency range from 0.8 Hz to 10,000 Hz. The wind speed was 5.6 m/s. The level reduction through switching off the turbine in a clearly broader spectral range can be seen.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 4.7-5 shows a comparison of the three measurement points for the low-frequency range from 1 Hz to 100 Hz. It must be noted that the background noise (wind, vegetation) is also included. This may vary at the respective measurement point. The wind speed at 10 m height during the averaging period was on average 5.6 m/s. At all measurement points, the ascertained levels were below the perception threshold at frequencies lower than 30 Hz. The levels in the area of infrasound fell clearly below the perception threshold.

INFLUENCE OF WIND SPEED

In order to investigate the dependency of low-frequency emissions on wind speed, numerous readings were recorded and graphically depicted in ***Figure 4.7-6***. The three charts represent the relationships at the measurement points at the distances 192 m, 305 m and 705 m.

The violet dots, which depict the lower value area, represent audible sound, expressed in dB(A). It can be seen clearly that the measured A levels are higher at a distance of 192 m (upper image) than at the measurement points further away. The A level at first increases with increasing wind speed.

The red dots represent the G-weighted sound level when the wind turbine is switched on, the green dots when the turbine is switched off. Similarly to the A level, it can also be seen for the G level that – despite higher scattering – it somewhat increases with increasing wind speed, and then remains constant (measurement point MP1).

The image above shows that at MP1, i.e. in the near field at a distance of 192 m from the turbine, the G-weighted sound pressure level during operation of WT 6 is significantly higher than the background noise when the turbine is off. This is much less pronounced at a distance of 305 m (centre image).

LEVEL DEVELOPMENT DURING THE MEASUREMENT

Figure 4.7-7 shows the A and G-weighted level development between 12:40 p.m. and 2:40 p.m. for the distances of 192 m and 705 m. In addition, the operating conditions of the wind power plant (green = turbine on, light blue = turbine off) as well as periods of extraneous noise (violet) are shown. For the two level developments of measurement point MP1, the operational phase "turbine off" is easily recognisable through the considerably declining level developments. At measurement point MP3, a level drop with the turbine switched off due to the fluctuating background noise is hardly recognisable.

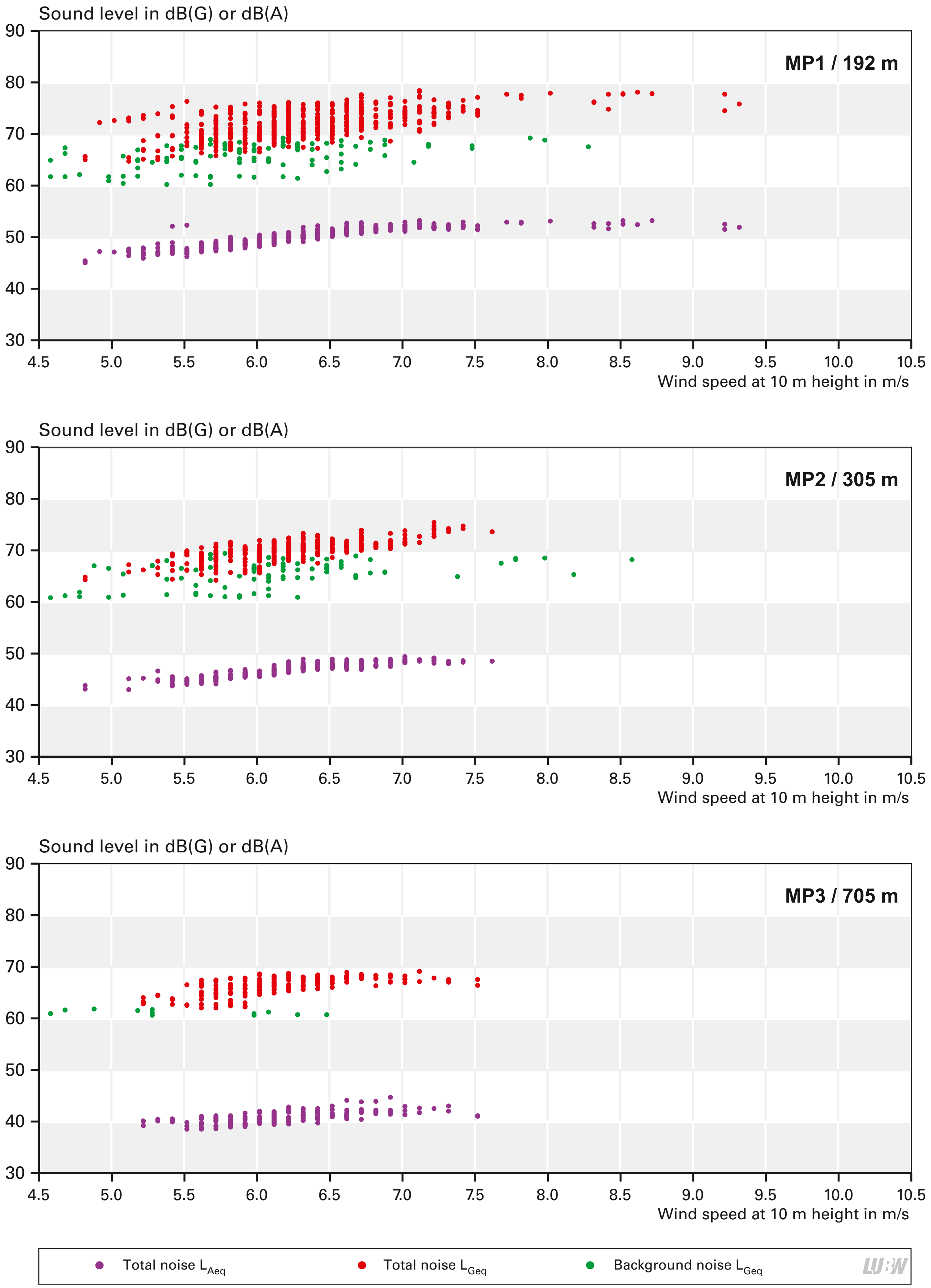


***Figure 4.7-6**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the wind turbine WT 6. The G levels when the turbine is switched on (red dots) and when the turbine is switched off (green dots) are shown, as are the A levels with the turbine switched on (violet dots).*

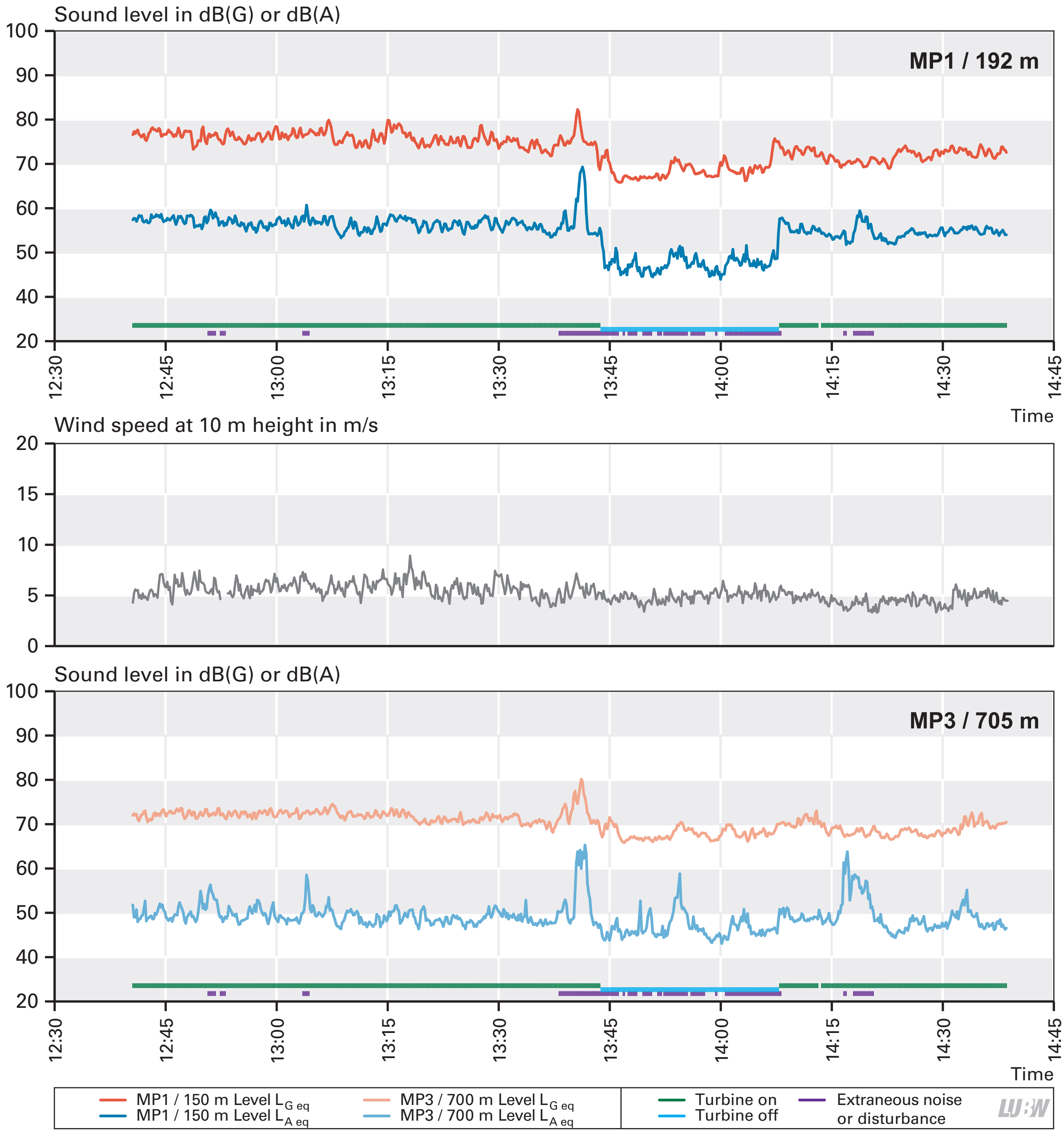


***Figure 4.7-7**: Chronological sequence of audible sound level (A level), infrasound level (G level), as well as the wind speed during the measurements of the wind turbine WT 6*

4.8 Vibrations at wind turbine 5: Nordex N117 – 2.4 MW

In order to determine a possible influence of the wind power plant on the surrounding area through vibration emissions, tremor measurements were carried out in addition to the sound assessments in the surrounding areas of wind turbine 5 (WT 5). The execution and analysis of the measurements was carried out in accordance with DIN 45669 [12] and DIN 4150 [13].

***Figure 4.8-1**: Vibration measurement point MP A at the tower foundation of WT 5. Photo: Wölfel company*

BASIC CONDITIONS

Wind turbine 5 (WT 5) is a unit by the company Nordex, type N117/2400, with a nominal generator capacity of 2.4 MW (see ***Figure 4.6-1***). The rotor diameter is 117 m, the hub height above ground is 140.6 m. The following is known about the building ground of the power plant: Up to a depth of 7 m there is cohesive ground (loam, weathering clay), which is judged to be not stable enough for the foundation of the power plant. Only after a depth of approx. 7 m is there Keuper rock, meaning that the foundation of the building structure or the load transfer has to be in this layer. It is not known whether this was accomplished with a pile foundation or a different procedure.

***Figure 4.8-2**: Vibration measurement point MP D on ground spike at a distance of 285 m from WT 5. Photo: Wölfel company*

The vibration measurement was carried out in all three spatial directions with the help of vibration sensors. The x axis was radially aligned to the tower, the y axis tangentially and z axis vertically aligned. Measurements were taken at the same time at the following locations:

- MP A directly at the tower near the outer wall of the wind turbine on concrete, see ***Figure 4.8-1***
- MP B at a distance of 32 m from the WT's exterior wall on a ground spike
- MP C at a distance of 64 m from the WT's exterior wall on a ground spike
- MP D at a distance of approx. 285 m from the WT's exterior wall on a ground spike, see ***Figure 4.8-2***

For the connection of the sensors by means of ground spikes to the ground, holes with a diameter of approximately 50 cm and a depth of 20 cm to 40 cm were dug into the ground.

The following operational states were registered during the measuring time:

- Operation of a wind turbine at wind speeds between approx. 6 and 12 m/s at a height of 10 m
- Switching off and subsequent restarting of the turbine
- Standstill of all wind power plants in the wind farm

During the measurement the wind turbine reached the maximum possible speeds starting from wind speeds of 6.6 m/s. Even at higher wind speeds no higher rotational speeds of the turbine are to be expected.

RESULTS

During the operation of the wind turbine, fluctuations in the signals were repeatedly seen, in particular at measurement point MP A directly by the tower. These can be attributed to individual gusts of wind. At the measurement points located farther away, these effects are less pronounced. A direct link between the changes in wind speed in the range of 6 to a maximum of 12 m/s and the vibrations in the ground cannot be seen. ***Table 4.8-1*** shows the ascer-

***Table 4.8-1**: Maximum values of the unweighted vibration velocities v in mm/s at the measurement points. The wind speeds measured at 10 m above ground level were between about 6 and 12 m/s.*

	MP A, at the tower		**MP B**, 32 m distance		**MP C**, 64 m distance		**MP D**, 285 m distance	
	z	x, y	z	x, y	z	x, y	z	x, y
Turbine on	0.5 - 1.0	0.30	0.03	0.08	0.02	0.04	< 0.01	0.01
Turbine off	0.04	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

tained maximum values of the unweighted vibration velocities v in mm/s for the different measurement points with uniform full load operation of the turbine. In the horizontal measurement directions the one with the highest value is stated; this was usually the x direction (radial, towards the tower).

Decreasing vibration velocity over the distance is shown graphically in ***Figure 4.8-3***. At the measurement point MP D at a distance of 285 m, the influence of the wind turbines is barely perceptible. For comparison, the spread calculated in accordance with [13] is also shown. When shutting down or restarting the turbine, the vibration level changes only slightly, see ***Figure 4.8-4***.

The evaluation of vibrational immissions with respect to possible exposure of people in buildings is carried out on the basis of DIN 4150 Part 2 [13]. The essential base parameter of this standard is the weighted vibration severity $KB_F(t)$. This is also an indication of the ability to sense vibrational effects. The perception threshold for most people lies in the area between $KB_F = 0.1$ and $KB_F = 0.2$. The KB_F value of 0.1 corresponds to an unweighted vibration velocity of approx. 0.15 to 0.30 mm/s. During the transition of tremors from the ground to building foundations there is usually a reduction of the vibration amplitudes. According to DIN 4150 Part 1, a factor of 0.5 should be taken. In the building itself, there may be an amplification, particularly if the excitation frequency is in the range of the ceiling's natural frequency. However, it is not expected that the effects established at the measurement point MP D could actually reach the level of the reference values according to DIN 4150 Part 2 in a building, since this would require an amplification by more than a factor of 20 within the building. At measurement point MP D at a distance of 285 m, mainly frequencies below 10 Hz were established, as shown in ***Figure 4.8-5***. In contrast, the natural frequencies for concrete ceilings in residential buildings are normally approx. 15 Hz to 35 Hz. For beamed ceilings, the natural frequencies are lower and can drop to approx. 10 Hz. Resonance excitation of the building ceilings can therefore not be expected.

CONCLUSION

The ground vibrations emanating from wind turbines can be detected by measurement. Already at a distance of less than 300 m from the turbine, they have dropped so far that they can no longer be differentiated from the permanently present background noise. No relevant vibrational effects can be expected at residential buildings.

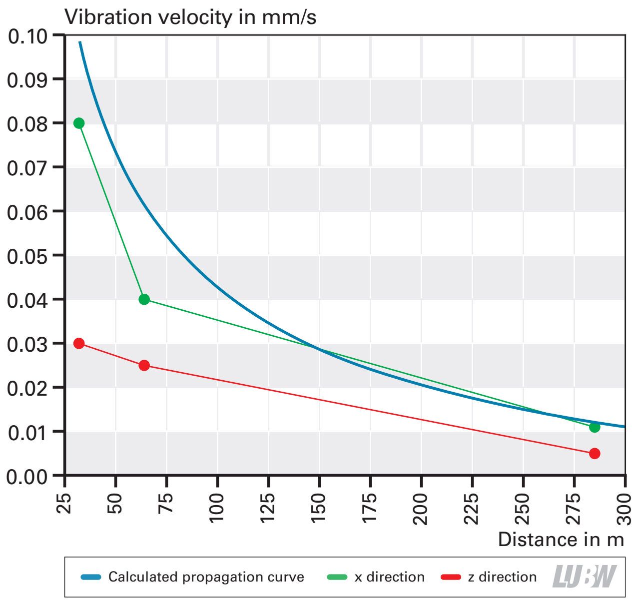


***Figure 4.8-3**: Comparison of prediction formula for [13] with the measured values*

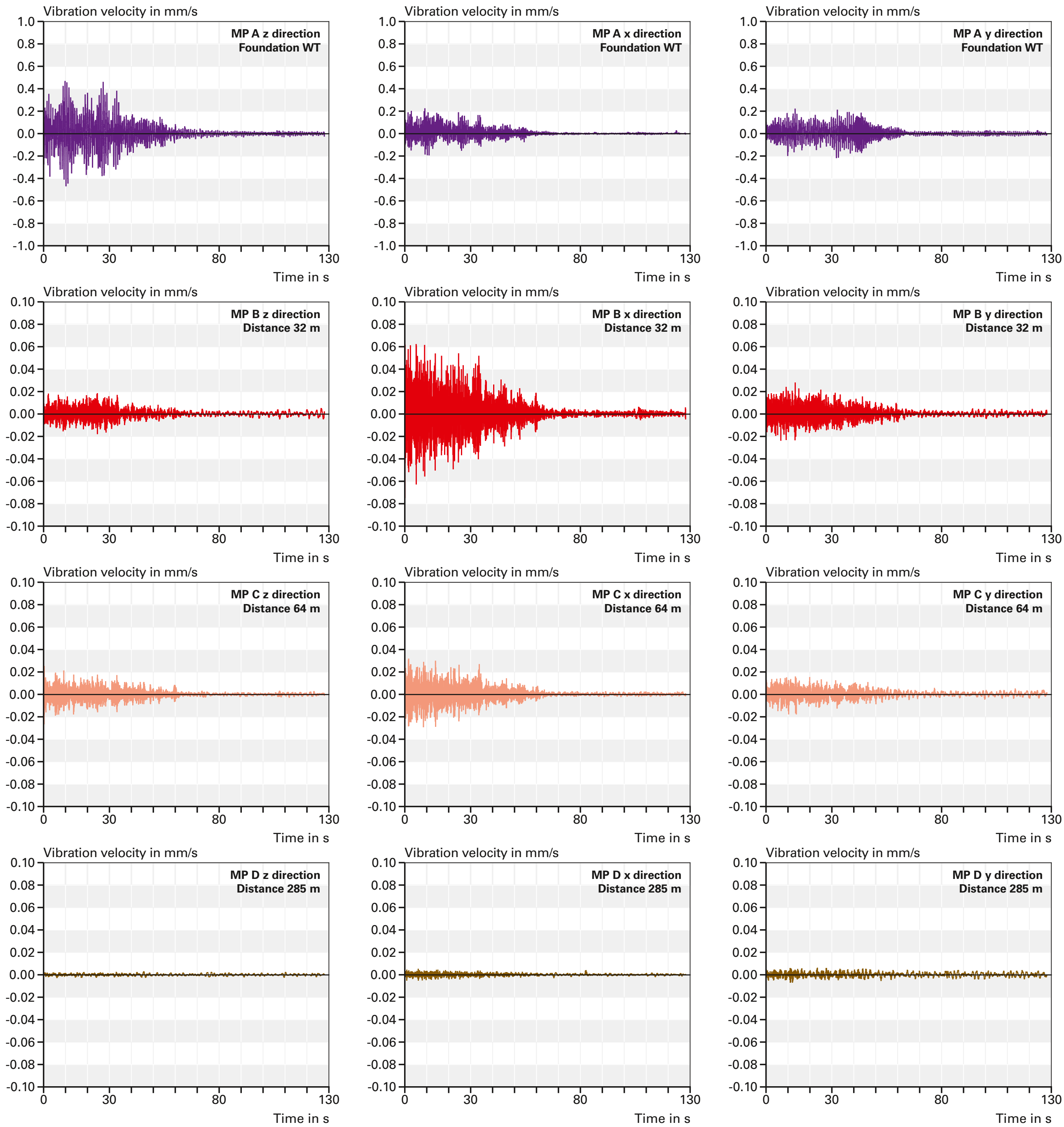


Figure 4.8-4: *Representation of the decreasing vibration after shutdown of the wind turbine 5 for all measurement points and directions. From top to bottom: Measurement points MP A to MP D; left to right: Spatial directions z, x and y. The shutdown of the turbine followed at 12:32 p.m. – Note the different scale of the vibration velocity at the measurement point MP A (foundation, top row).*

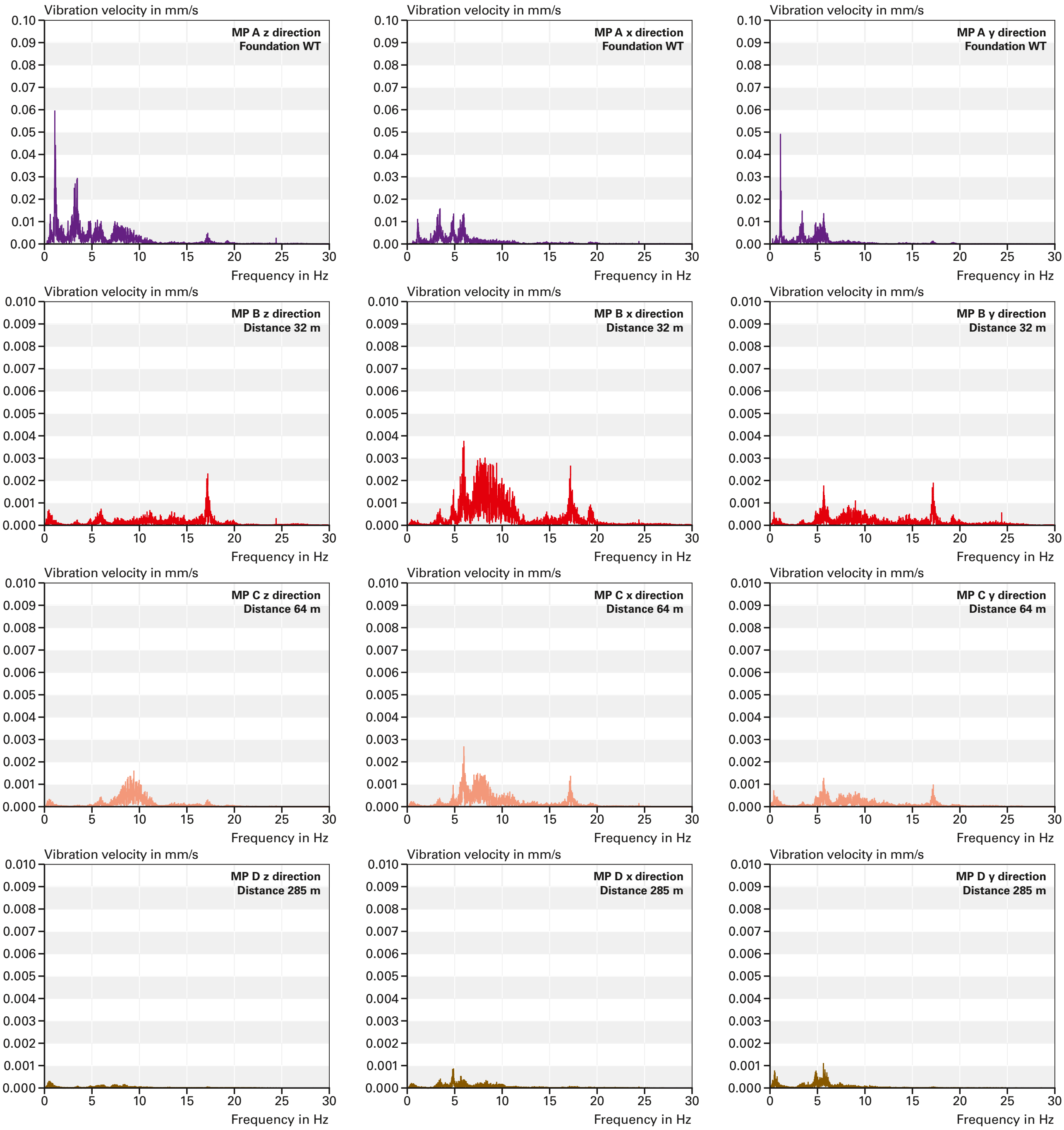


Figure 4.8-5: *Representation of the frequency spectrum of the vibrations with uniform operation of the wind turbine 5 for all measurement points and directions. The measurement was taken at 11:12 a.m. at a wind speed of approx. 8 m/s at a height of 10 m. From top to bottom: Measurement points MP A to MP D; left to right: Spatial directions z, x and y. – Note the different scale of the vibration velocity at the measurement point MP A (foundation, top row).*

4.9 Measurement results from literature

In the following a few previously available, publicly accessible measurement results about infrasound and low-frequency noise at wind turbines shall be briefly discussed. Overall, the amount of available worldwide publications on this issue is modest but not low. The publications presented here partially refer to many other references. In this selection we have aimed to introduce German-speaking publications (Mecklenburg-Western Pomerania, Bavaria) as well as important European (Denmark) and international (Australia) studies and measurement programmes. However, the report at hand is no literature study, meaning that a restriction is necessary.

MECKLENBURG-WESTERN POMERANIA

The company Kötter Consulting, Rheine, carried out emissions and immissions measurements in 2005 and 2009 on behalf of the Federal State of Mecklenburg-Western Pomerania, State Office for the Environment, Nature Conservation and Geotechnology (LUNG) at a wind farm that contained a total of 14 turbines. The report is publicly available [14]. In summary, the authors come to the following conclusions:

- "The results of the emission measurement [...] show that at frequencies in the infrasound range at f < 10 Hz, the individual operating states cannot be distinguished from one another. Moreover, the dispersion of the sound pressure level is high." See ***Figure 4.9-1***.
- "In terms of emissions, however, the different operating states in the low-frequency range (16 Hz < f < 60 Hz) are metrologically detectable, whereas at the immission location, the turbine noise is indistinguishable from background noise."
- "The results of immission measurements show [...] that the reference values for the evaluation of low-frequency noise according to Supplement 1 of DIN 45680 [4] [...] are also complied with."
- "In terms of immissions, no noteworthy difference is perceivable between the operating state ‚all WT on' and background noise. The readings are clearly below the hearing threshold level curve in the infrasound range." See ***Figure 4.9-2***.

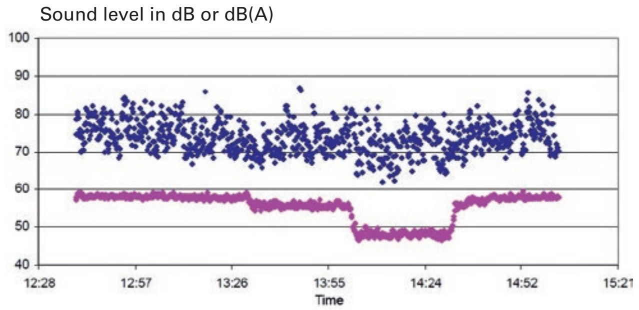


Figure 4.9-1*: Chronological sequence of level at the emission location (outside) near the turbine. The lower, magenta curve represents the sequence of the A-weighted audible noise level. The clearly identifiable gradual decrease in the sound level correlates with the various operating states (far left all turbines on, then two turbines off, then all turbines off). At the end, the A-weighted sound level increases again when all turbines are turned on (far right). Remarkably, the 8 Hz infrasound level hardly changes at all (blue, greater scattering of dots). The measurement report also includes illustrations for 20 Hz and 63 Hz; with these low frequencies, the operating conditions could be registered in the near field. Source: [14], Figure 9, page 24, details added.*

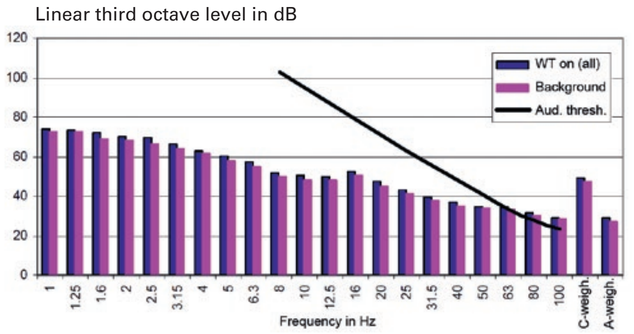


Figure 4.9-2*: Immission: Display of lower frequency levels subject to third octave frequency within a residential building at a distance of 600 m. No significant difference can be seen between the operating states "all WT on" and the background noise. The readings are clearly below the hearing threshold curve in the infrasound range. Source: [14], Figure 21, page 33*

BAVARIA

The Bavarian State Office for the Environment (LfU) carried out a long-term noise immission measurement from 1998 to 1999 at a 1 MW wind turbine of the type Nordex N54 in Wiggensbach near Kempten. ***Table 4.9-1*** and ***Figure 4.9-3*** show the main results. The study concludes that "the noise emissions of the wind turbine in the infrasound range are well below the perception threshold of humans and therefore lead to no burden". Furthermore, it was found that the infrasound caused by the wind is significantly stronger than the infrasound generated by the wind turbine alone [15] [16].

DENMARK

A Danish study from 2010 [17], in which data from almost 50 wind turbines with outputs between 80 kW and 3.6 MW was evaluated, comes to the following conclusion: "Wind power plants do certainly emit infrasound, but the levels are low when taking into account the human sensitivity to such frequencies. Even close up to the wind power plants, the sound pressure level is far below the normal auditory threshold, and the infrasound is therefore not seen as a problem for wind power plants of the same type and size as the ones examined" [15]. Further international publications on the issue are quoted in the study.

AUSTRALIA

In 2013 the Enviroment Protection Authorithy South Australia and the engineering company Resonate Acoustics published the study "Infrasound levels near windfarms and in other environments" [18]. The study includes results of measurements taken both outside as well as indoors. The measurement points were in close proximity to windparks and in regions without wind power plants.

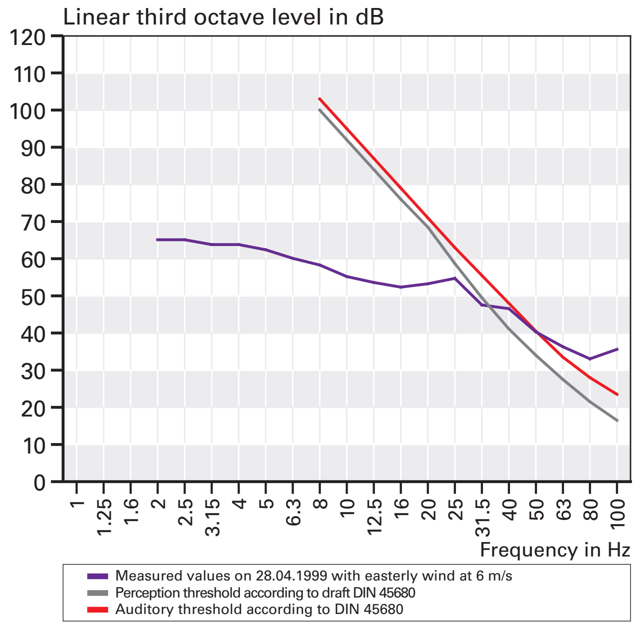


Figure 4.9-3*: The examined wind turbine causes sound waves that can be heard only above 40 Hz by a person standing on a balcony at a distance of 250 m. The infrasound range is not perceptible, since it lies clearly below the perception threshold. Source: [15]*

In summary, it was stated that the measured infrasound expositions, which were measured in close proximity to windfarms in residential buildings, correspond to the levels determined in comparable regions without wind power plants. The lowest infrasound levels determined in the measuring project were registered in a house standing in the proximity of a wind park.

The infrasound levels in close proximity to wind power plants are not higher than in other urban and rural regions, in which the contribution of wind power plants is negligible, compared to the background level of infrasound in those areas.

Table 4.9-1*: Infrasound level at a distance of 250 m from a 1 MW wind turbine with different wind velocities. Source: [15]*

Wind velocity		Linear third octave level in dB with a third octave centre frequency of				
		8 Hz	10 Hz	12.5 Hz	16 Hz	20 Hz
6 m/s	Breeze, the measured sound comes primarily from the wind turbine	58	55	54	52	53
15 m/s	Strong to stormy wind, the measured sound comes primarily from the wind	75	74	73	72	70

Quotation: "It is clear from the results that the infrasound levels measured at the two residential locations near wind farms (Location 8 near the Bluff Wind Farm and Location 9 near Clements Gap Wind Farm) are within the range of infrasound levels measured at comparable locations away from wind farms. Of particular note, the results at one of the houses near a wind farm (Location 8) are the lowest infrasound levels measured at any of the 11 locations included in this study. This study concludes that the level of infrasound at houses near the wind turbines assessed is no greater than that experienced in other urban and rural environments, and that the contribution of wind turbines to the measured infrasound levels is insignificant in comparison with the background level of infrasound in the environment". [18]

4.10 Conclusion of the measurements at wind turbines

- The low-frequency noise including infrasound measured in the vicinity of wind turbines consists of three parts: 1. Turbine noise; 2. Noise that results from the wind in the surrounding area; 3. Noise that is induced at the microphone by the wind. Wind always has to be considered as an interference factor (extraneous noise) when determining the turbine noise. The measured values are subject to a wide spread.

- The infrasound being emanated from wind turbines can generally be measured well in the direct vicinity. Below 8 Hz discrete lines appear in the frequency spectrum as expected, which are attributable to the constant movement of the individual rotor blades.

- At a distance of 700 m from the wind turbines, it was observed that when the turbine is switched on, the measured infrasound level did not increase notably or only increase to a limited extent. The infrasound was generated mainly by the wind and not by the wind turbines.

- The measured infrasound levels (G levels) at a distance of approx. 150 m from the turbine were between 55 and 80 dB(G) with the turbine running. With the turbine switched off, they were between 50 and 75 dB(G). At distances of 650 to 700 m, the G levels were between 55 and 75 dB(G) with the turbine switched on as well as off. A cause for the spread of the values is the strongly varying proportions of noise, which are caused by the wind (***Table 2-1***).

- For the measurements carried out even at close range, the infrasound levels in the vicinity of wind turbines – at distances between 150 and 300 m – were well below the threshold of what humans can perceive in accordance with DIN 45680 (2013 Draft) [5] or ***Table A3-1***.

- The vibrations caused by the wind turbine being examined were already minimal at a distance of less than 300 m. At distances as prescribed for reasons of noise pollution protection, no exposures that exceed the pervasive background noise are to be expected at residential buildings.

- The results of this measurement project comply with the results of similar investigations on a national and international level.

Table 4-11*: Tabular representation summing up the first measured values (infrasound and low-frequency noise) at wind turbines. The measured values were frequently subject to substantial fluctuations and always also contain wind noises. Since the measurements were carried out with a reverberant plate, a correction took place (see. Section 4.1).*

Wind turbine (WT)		Section	G-weighted level in dB(G) **WT on / off**	Infrasound third octave level ≤ 20 Hz in dB * **WT on**	Low-frequency third octave level 25-80 Hz in dB * **WT on**
WT 1	– 700 m – 150 m	4.2	55-75 / 50-75 65-75 / 50-70	– 55-70	– 50-55
WT 2	– 240 m – 120 m	4.3	60-75 / 60-75 60-80 / 60-75	– 60-75	– 50-55
WT 3	– 300 m – 180 m	4.4	55-80 / 50-75 55-75 / 50-75	– 50-70	– 45-50
WT 4	– 650 m – 180 m	4.5	50-65 / 50-65 55-65 / 50-65	– 45-55	– 40-45
WT 5	– 650 m – 185 m	4.6	60-70 / 55-65 60-70 / 55-65	– 50-65	– 45-50
WT 6	– 705 m – 192 m	4.7	55-65 / 55-60 60-75 / 55-65	– 55-65	– 45-50

* Linear third octave level in dB(Z)

5 Traffic

Within the context of the measurement project, not only wind turbines but also other sources of low-frequency sound incl. infrasound were to be examined. An obvious choice was to investigate the pretty-much ubiquitous road traffic. For this purpose, measurements was carried out at a road in Würzburg (by the company Wölfel) as well as at the federal motorway A5 south of Karlsruhe (by the LUBW). In addition, data from the inner-city continuous traffic noise measuring stations of the LUBW in Karlsruhe and Reutlingen was used, in order to assess the recorded data with respect to low-frequency noise incl. infrasound. The conditions were selected in such a way that neither wind noises in the vicinity nor wind-induced noises at the microphones arose, which can cause problems during the measurements at the wind turbines (see Section 4). The results represented in the following are therefore to be causally attributed to road traffic.

5.1 Inner-city roads – measurement in Würzburg

At the immission location of Rottendorfer Strasse in Würzburg it was possible to carry out the noise level measurements with a special focus on low-frequency noise and infrasound inside as well as outside of a residential building. The measurement point is predominantly in the direct sphere of influence of Rottendorfer Strasse, but also within the sphere of the federal road B 19, which leads from Bad Mergentheim to Würzburg, as well as the railway line Würzburg-Lauda (***Figure 5.1-1***). However, at the immission location, the noise from the road traffic on the Rottendorfer Strasse dominates (***Figure 5.1-2***), with an average traffic volume of 13,971 motor vehicles in 24 hours with a proportion of heavy goods traffic of approx. 3 % (data from the 2012 traffic survey).

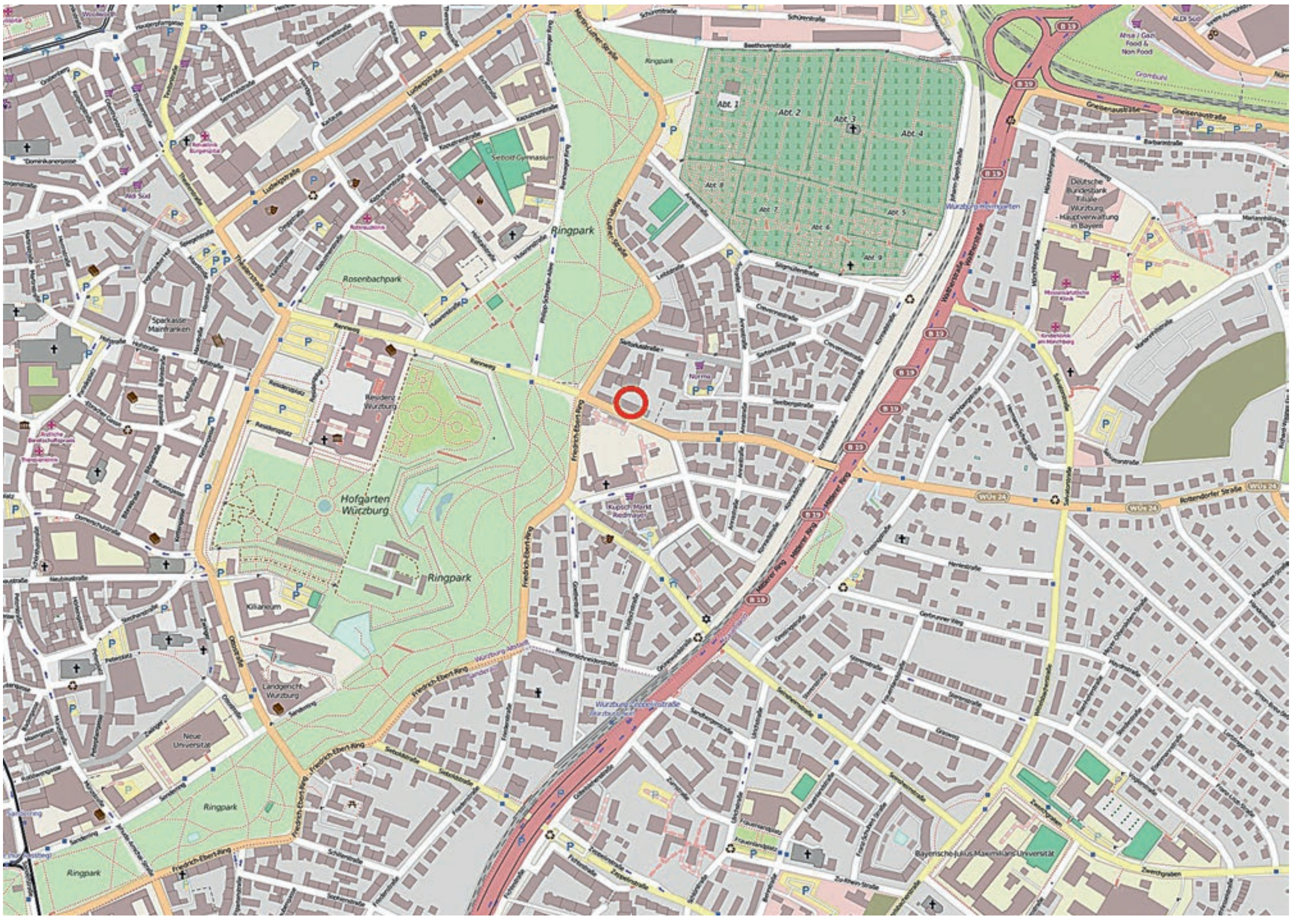


Figure 5.1-1*: Layout plan showing the immission location at Rottendorfer Strasse, Würzburg. Source: www.openstreetmap.org*

Figure 5.1-2 a/b: *View along Rottendorfer Strasse in Würzburg. Photo: Wölfel company*

A situation as can be found in many places was specifically selected. At measurement points with very high volumes of traffic and the thus associated traffic noise, the audible noise level is prioritised; this can already lead to situations that are a nuisance and possibly also harmful environmental effects. The low-frequency noise, incl. its share of infrasound, eminating from the road traffic could be measured without any disturbing wind noises. The measured levels are characteristic for the noise situation in the residential area.

The sound pressure level up to a lower threshold frequency of 1 Hz was measured at one measurement point in the open and one measurement point in a residential building. For the evaluation of the low-frequency effects, evaluations according to DIN 45680 (2013 draft) [5] were carried out for the measurement point within the building.

The execution of the measurement took place at two measuring locations. Measurement point MP1 was selected in accordance with DIN 45645 (1996) [8] and – in the same manner as the measurements at the wind turbines – with reverberant plate on the ground of the balcony facing the road. A second measurement point MP2 was located within the building in accordance with DIN 45680 (March 1997) [4]. The measurement was carried out as an observed measurement. The fully furnished and inhabited flat was not used during the measuring time. The size of the room was approx. 7.6 m x 4.3 m x 2.5 m. An informatively comparative measurement was carried out at a third measurement point located directly on the façade at the height of the windows. The third octave levels on the façade in the range below 25 Hz are between 0 and 3 dB lower than the third octave level on the floor of the balcony. Within the range between 25 Hz and 80 Hz, the third octave levels directly at the façade are up to 6 dB lower than the third octave levels on the floor of the balcony. In the frequency range above 100 Hz, on the other hand, they are 0 to 3 dB higher than the third octave levels on the floor of the balcony. The measuring data presented here for the floor of the balcony was not subjected to level corrections according to Section 4.1.

The measurement period extended from Thursday afternoon, 04.07.2013, 3:00 p.m., to the early morning of the following Friday, 05.07.2013, 6:00 a.m. The measuring period was not during the school holidays and is representative for the burden of the immission location on a working day. The traffic volume is estimated as being comparable to the data of the traffic survey. During the measurement of traffic noise, the periods with significant external noise exposure (e.g. flight noise, animal sounds and noises by the measuring engineer) were marked and excluded from the analysis. The measurements were performed in a wind speed range of 0 to 4 m/s (a mean value of 0.5 m/s), a temperature range of 16.3 to 22.5 °C, and an air pressure range of 999 to 1,003 hPa.

RESULTS AT OUTDOOR MEASUREMENT POINT

As an example, third octave spectra for the time periods 4:00 p.m. - 5:00 p.m., 10:00 p.m. - 11:00 p.m. and 12:00 a.m. - 1:00 a.m. are presented in ***Figure 5.1-3*** for the measurement point MP1 (outside the building). The outside daytime levels in the low-frequency range were up to 100 Hz above the hearing or perception threshold. A significant peak in the frequency range 25 Hz to 80 Hz can be seen in the third octave spectra, which is due to vehicle traffic. In the area of 25 Hz to 63 Hz, the levels exceed 70 dB, partially up to 75 dB. At night, values of up to 65 dB are reached. For the infrasound up to 20 Hz, the outdoor daytime levels were below the hearing or perception threshold between 45 and 65 dB. The specified frequencies refer to the third octave centre frequency.

Figure 5.1-4 shows the one hour average linear third octave level for the low-frequency range below 100 Hz compared to the perception threshold in accordance with DIN 45680 (2013 draft) [5]. For values below 8 Hz, this was amended [11], see also ***Table A3-1***. The correlation of the values with the traffic situation is clearly recognisable: The heavier road traffic between 4:00 p.m. to 5:00 p.m. leads to higher values both in the infrasound range as well as in the other low-frequency ranges. Depending on the traffic volume, the perception threshold is exceeded between 20 Hz and 32 Hz (third octave centre frequency).

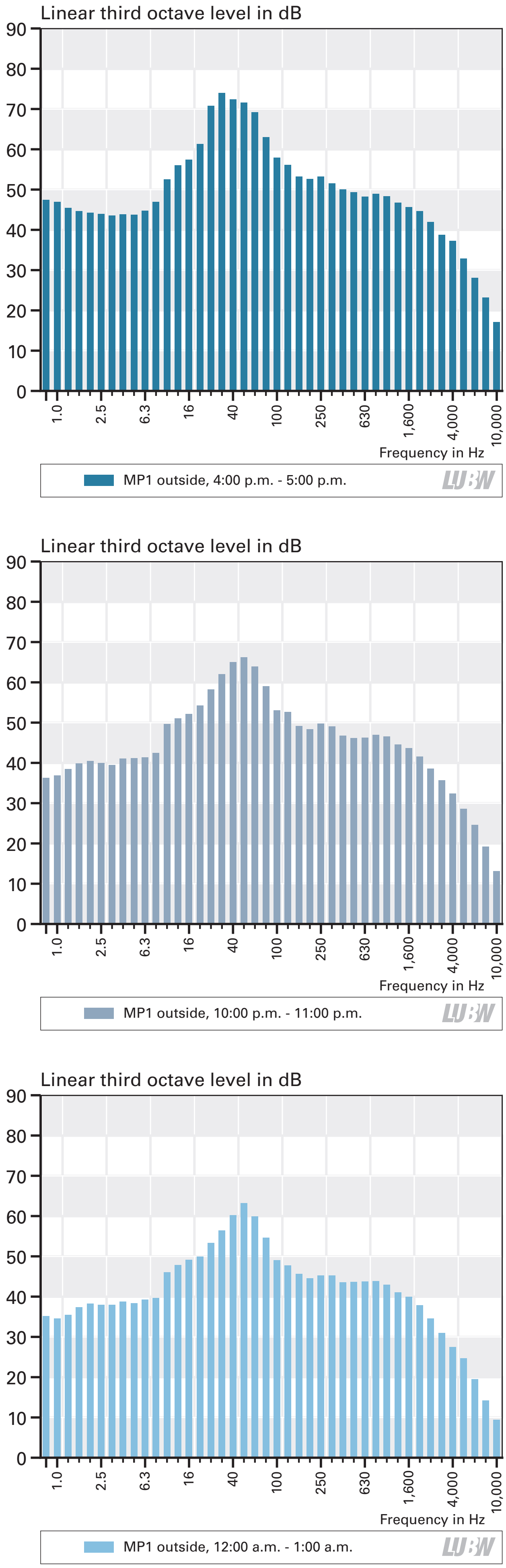


Figure 5.1-3: *Linear third octave spectra for the periods 4:00 p.m. - 5:00 p.m. (top), 10:00 p.m. - 11:00 p.m. (centre) and 12:00 a.m. - 1:00 a.m. (below) at the outside measurement point MP1. A significant peak in the frequency range 25 Hz to 80 Hz can be seen for the spectra, which is due to vehicle traffic.*

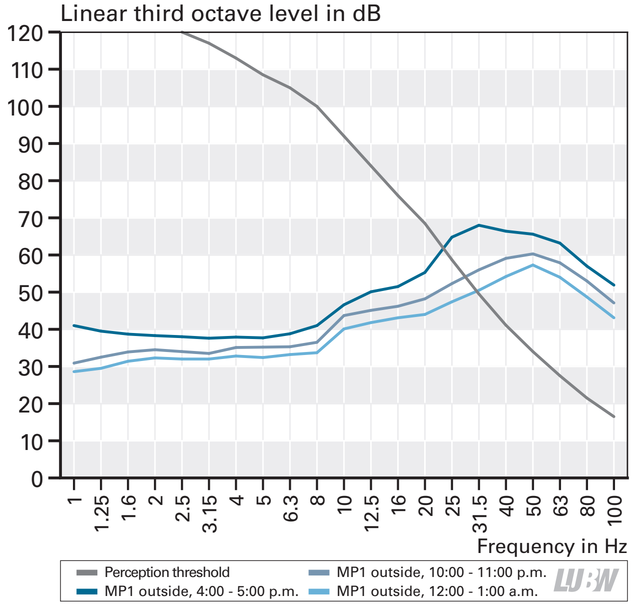


***Figure 5.1-4**: Comparison of the corrected linear third octave levels, determined at the measurement point MP1 (outside the building) for the averaging periods 4:00 - 5:00 p.m., 10:00 - 11:00 p.m., and 12:00 - 1:00 a.m. Furthermore, the perception threshold is also shown (see Section 4.1).*

The A and G-weighted sum level LAeq(t) and LGeq(t) recorded during the entire measuring period are shown in ***Figure 5.1-5***. While the A-weighting shows the audible sound as a single number value, the valuation focus of the G level is in the infrasound range. The curves show a significant bandwidth that is created by the variations of the sound influences. These variations are less pronounced for the G level. The relationship of the courses of the A and G levels can also be clearly seen. Both levels are significantly reduced at night, when there is less traffic. The G level reaches values of up to 80 dB (G) at daytime and minimum values of around 55 dB (G) at night, with strong fluctuations.

RESULTS AT INDOOR MEASUREMENT POINT

The third octave spectra for the time periods 4:00 p.m. - 5:00 p.m., 10:00 p.m. - 11:00 p.m. and 12:00 a.m. - 1:00 a.m. are presented in ***Figure 5.1-6*** for the measurement point MP2 inside the building. The interior levels for infrasound up to 20 Hz are below the hearing or perception threshold (< 55 dB) at day and night. Above 32 Hz to 40 Hz (third octave centre frequency), the values of the linear third octave level are above the hearing or perception threshold (up to 55 dB). In narrowband spectra (not shown here) a number of discrete, prominent maxima were detected, which were attributable to natural frequencies of the room and excited natural frequencies of the building.

Figure 5.1-7 shows the one hour average linear third octave level for the low-frequency range below 100 Hz compared to the perception threshold in accordance with DIN 45680 [5]. This was amended for values below 8 Hz [11]. In general, a decrease in the level can be seen the later it gets. Why

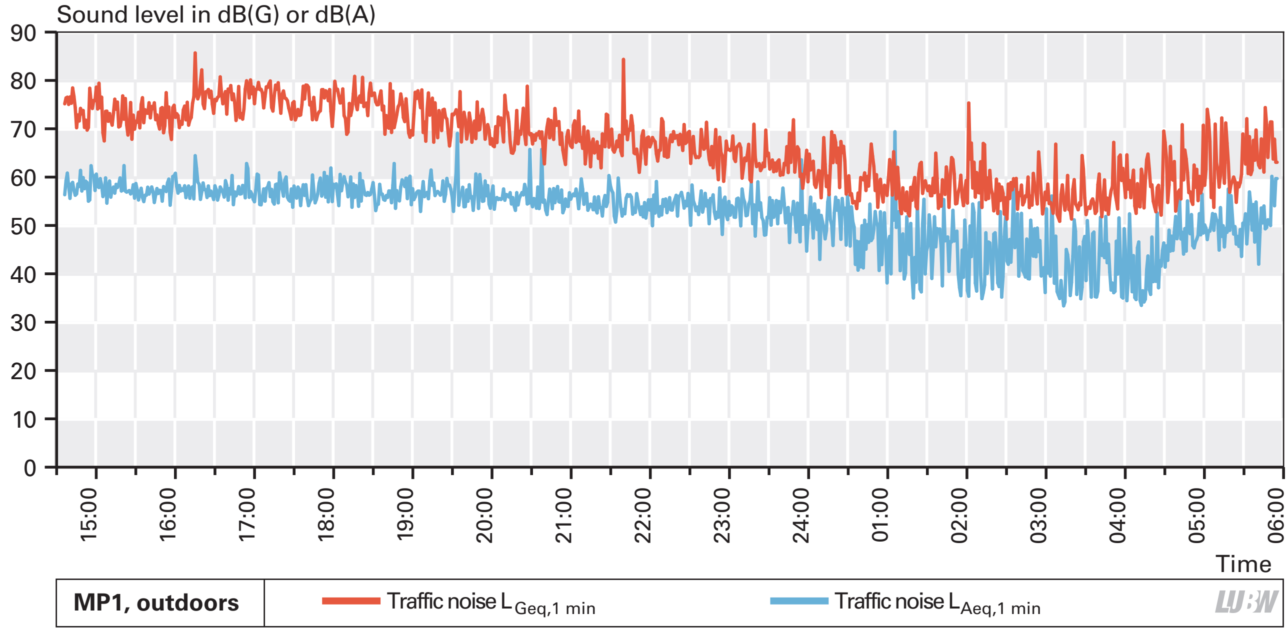
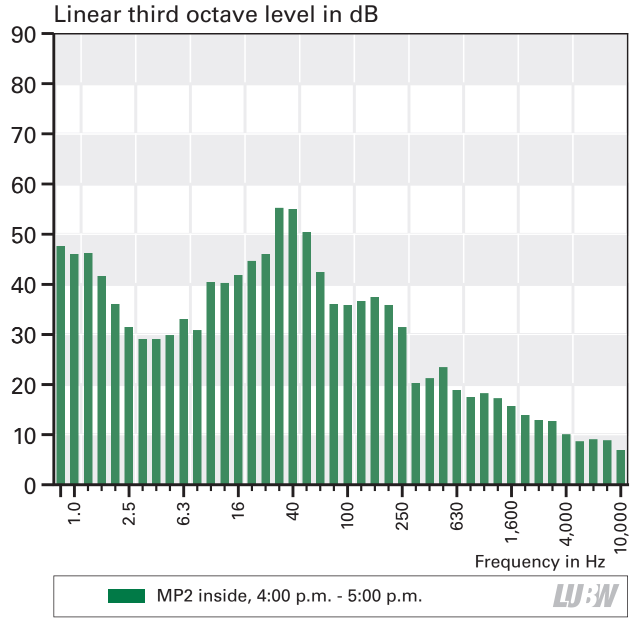
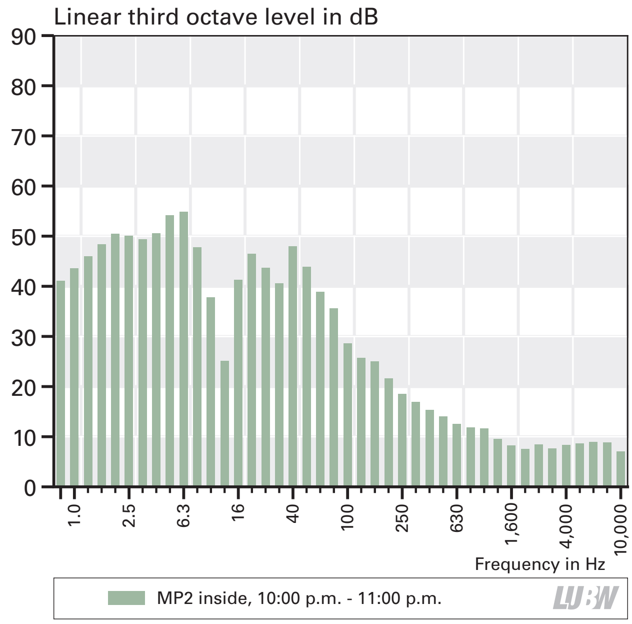


***Figure 5.1-5**: Distribution of the A-weighted sum level $L_{Aeq(t)}$ (blue) and the G-weighted sum level $L_{Geq(t)}$ (red) over the entire measurement period at the outdoor measurement point MP1*



the infrasound levels between 2 Hz and 8 Hz are higher at night is unclear. The G-weighted level during the time elapsed was between 40 dB(G) at night and 65 dB(G) at day.



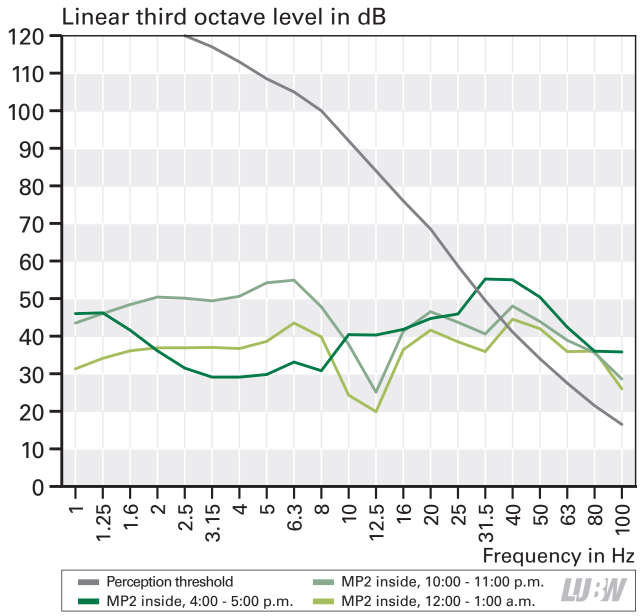


Figure 5.1-7 *(top): Comparison of the third octave levels at the measurement point MP2 (indoors) for the averaging periods 4:00 - 5:00 p.m., 10:00 - 11:00 p.m. and 12:00 - 1:00 a.m. The perception threshold according to Table A3-1 is also shown.*

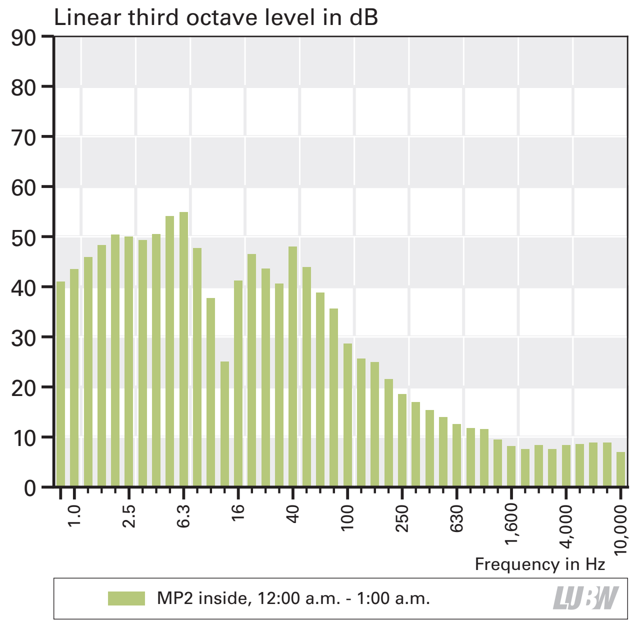


Figure 5.1-6 *(left column): Linear third octave spectra for the time periods 4:00 - 5:00 p.m. (top), 10:00 - 11:00 p.m. (centre) and 12:00 - 1:00 a.m. (bottom) at the indoor measurement point MP2.*

5.2 Inner-city roads – permanent measuring stations Karlsruhe and Reutlingen

Since November 2012, the LUBW has been running a stationary road traffic noise monitoring station in Karlsruhe (Reinhold-Frank Strasse), and a further one in Reutlingen (Lederstrasse-Ost) since March 2013. This is where average and maximum levels of total noise are measured with the use of high-quality sound level measurement devices, as well as meteorological parameters such as temperature, wind speed and precipitation. In addition, the traffic data (vehicle type, quantity and speed) are recorded. Both stations are in areas with relatively high volumes of traffic: In Karlsruhe, approximately 24,000 vehicles/24h, however with a partial standstill of traffic, and in Reutlingen approximately 50,000 vehicles/24h (as of 2011).

In Karlsruhe, the microphone is positioned close to the road, meaning that the recorded levels do not directly depict the concerns of the population living somewhat further away. The distance to residential buildings is less than 10 m (***Figure 5.2-1***). The location of the measuring station in Reutlingen allows immediate statements to be made about the noise pollution for the people affected (***Figure 5.2-2***). Further information is available on the website www.lubw.de/aktuelle-messwerte (home page). The annual reports by the LUBW for the traffic noise monitoring stations can be found under the heading "Auswertungen" (Reports).

Based on the measurement data of the road traffic noise measuring stations in Karlsruhe and Reutlingen, evaluations were made by us with regards to low-frequency noise (incl. infrasound). In the following ***Figures 5.2-3 and 5.2-4*** frequency-selective representations of the noise level from 6.3 Hz to 125 Hz (third octave centre frequency) can be found for the two stations. Averaging was carried out over 30 minutes and summarized. Here only those time periods have been considered in which the wind speeds were less than one meter per second. These were approx. 2,000 half-hour averages for Karlsruhe and about 1,900 for Reutlingen, including many night hours. This avoided the occurrence and subsequent measurement of noise in the vicinity caused by the wind, and also ensured that no sound induced by the wind occurred directly at the microphone. Both

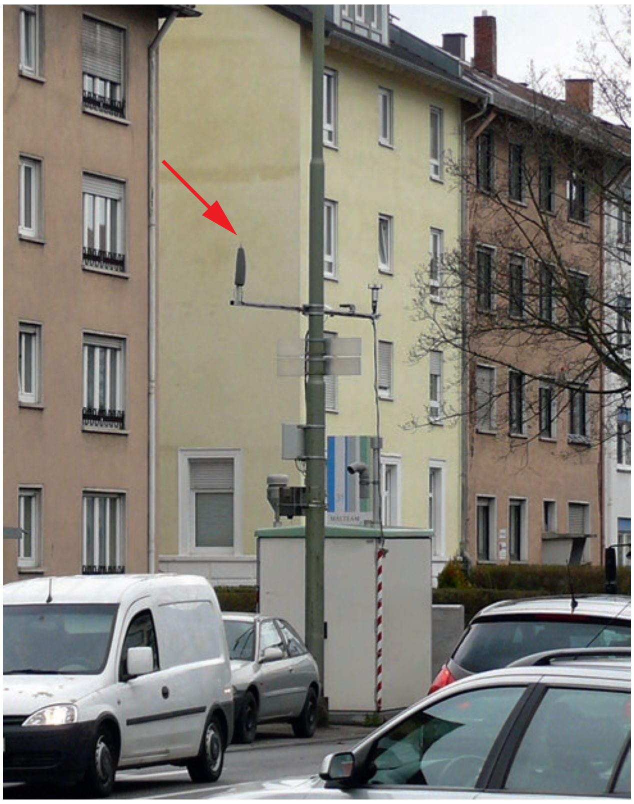


Figure 5.2-1: *LUBW measuring station for detecting road traffic noise in Karlsruhe, Reinhold-Frank-Strasse. The arrow shows the location of the microphone. Residential buildings visible in the background. Photo: LUBW*

Figure 5.2-2: *LUBW measuring station for detecting road traffic noise in Reutlingen, Lederstrasse. The arrow shows the location of the microphone. Photo: LUBW*

effects would have led to an increase in the level values at low frequencies and infrasound, as was the case during the measurements at the wind turbines.

To show the influence of traffic density, illustrations for higher and lower traffic volumes as well as for an average amount of traffic have been added (the exact data is given from the legend of ***Figure 5.2-3 and 5.2-4***). The proportion of heavy-goods traffic, based on the evaluated overall data, was 5 % in Karlsruhe and 11 % in Reutlingen.

Both evaluations show a striking increase between 31.5 Hz and 80 Hz above the perception threshold, which is attributable to motor vehicle traffic. Depending on traffic intensity, mean values of 72 dB (Karlsruhe) or 75 dB (Reutlingen) are reached. In the infrasound range (below 20 Hz) and below, the results of the measurements differ: This is where in Karlsruhe lower values are measured than in Reutlingen, which is probably due to different amounts of heavy-goods traffic, traffic volumes and speeds. In both cases, the third octave levels already exceed the perception threshold with a higher traffic volume between the 20 Hz and 25 Hz third. A similar result was at hand for the road measurement in Würzburg (Section 5.1, ***Figure 5.1-4***). The G-weighted sound levels were between 65 and 75 dB(G) in Karlsruhe and between 70 to 80 dB(G) in Reutlingen, see ***Table 5.2-1***.

5.3 Motorway – measurement near Malsch

The LUBW undertook sound measurements at the A5 (E52) motorway south of Karlsruhe near the town of Malsch on 26.06.2013 during the daytime between 1:00 p.m. and 3:00 p.m. The weather was sunny and practically windless. Wind-induced interfering noise at the microphone can therefore be ruled out. The distances of the microphone position to the middle of the centre strip of the motorway were 80 m, 260 m and 500 m (***Figure 5.3-1***). The measurement values at the measurement point at a distance of 500 m later had to be rejected due to the interference of the B3 main road and other interfering noise. Information on the used metrology can be found in Appendix A4.

The measurement results for the distances of 80 m and 260 m are graphically presented in ***Figure 5.3-2*** as a third

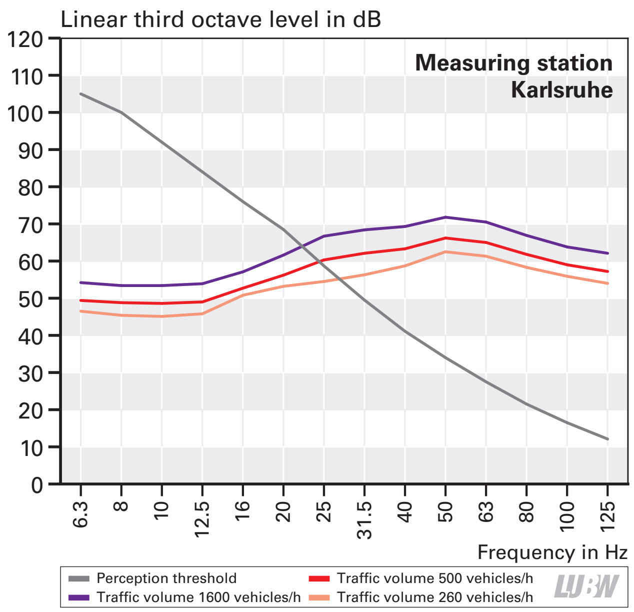


Figure 5.2-3: *Third octave spectra, measuring station Karlsruhe*

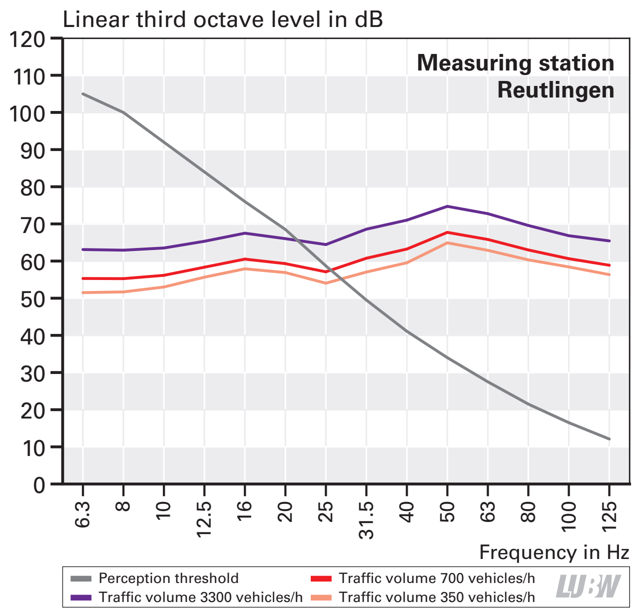


Figure 5.2-4: *Third octave spectra, measuring station Reutlingen*

Periods with zero wind or wind velocities below 1 m/s in the year 2013 were evaluated. Averages over 30 minutes each were formed and aggregated. The increased level in the range between the 31.5 Hz and 80 Hz thirds is caused by road traffic. The curves show the differences at various traffic volumes. Note: The representation begins at a frequency of 6.3 Hz (in other illustrations partly from 1 Hz.); this is due to the measuring technology. For comparison, the perception threshold according to Table A3-1 is shown.

***Table 5.2-1**: Summary of the measurement results for low-frequency noise (including parts of infrasound) at the traffic noise monitoring stations Reutlingen and Karlsruhe*

Source/situation	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB *	Low-frequency third octave levels 25-80 Hz in dB *
Traffic noise measuring station Karlsruhe traffic volume >1600 vehicles/h	75	53 to 62	67 to 72
Traffic noise measuring station Karlsruhe average traffic volume: 500 vehicles/h	65	48 to 57	60 to 67
Traffic noise measuring station Karlsruhe traffic volume < 260 vehicles/h	69	45 to 54	55 to 63
Traffic noise measuring station Reutlingen traffic volume > 3300 vehicles/h	80	63 to 68	64 to 75
Traffic noise measuring station Reutlingen average traffic volume: 700 vehicles/h	70	55 to 61	57 to 68
Traffic noise measuring station Reutlingen traffic volume < 350 vehicles/h	73	52 to 57	54 to 61

* Linear third octave level in dB(Z)

LUBW

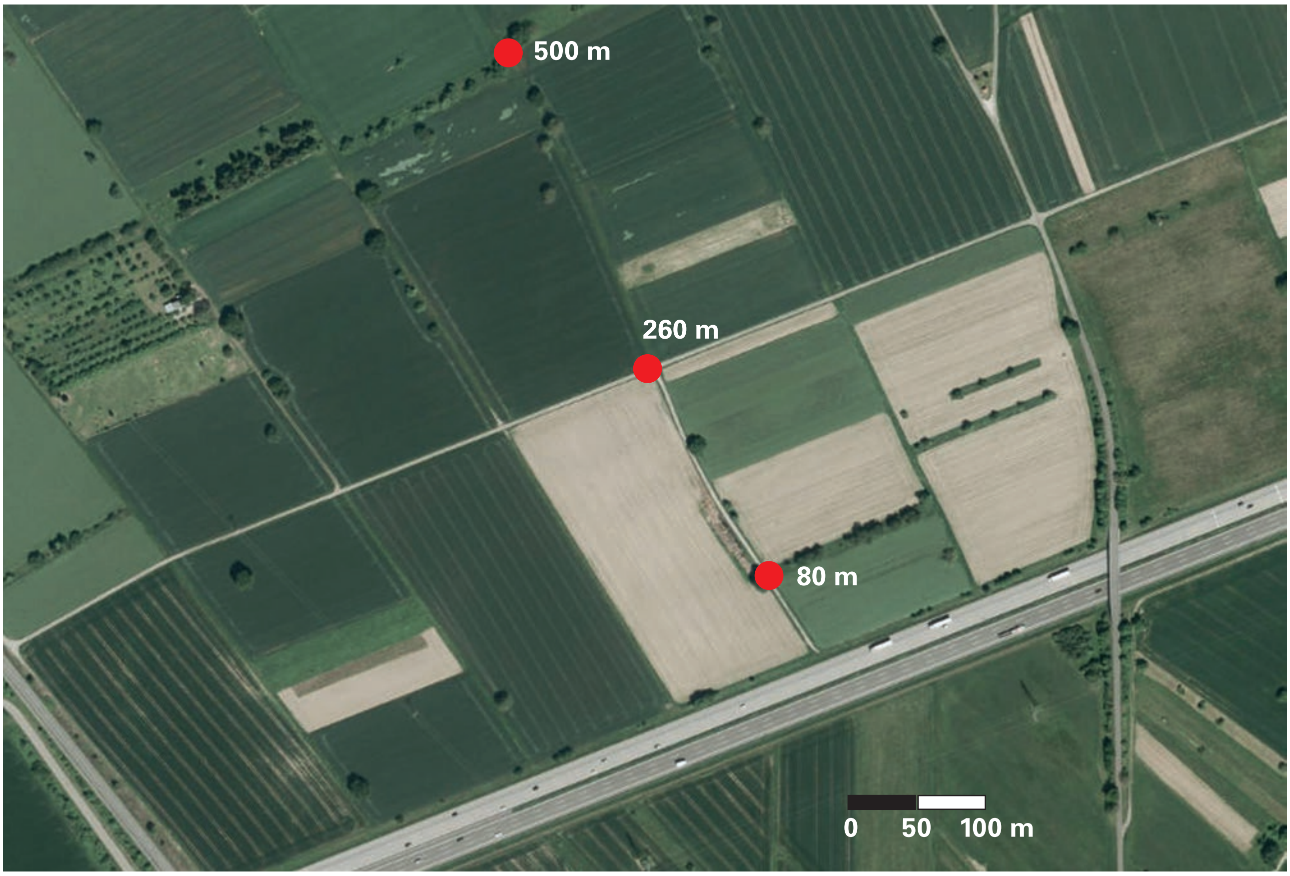


***Figure 5.3-1**: Location of the measurement points at the A5 motorway south of Karlsruhe near Malsch, indicating the distances between the microphone positions and the centre of the motorway. The town of Malsch is located outside of the picture at the bottom left. The B3 main road is located above the picture. Picture source: LUBW, LGL*

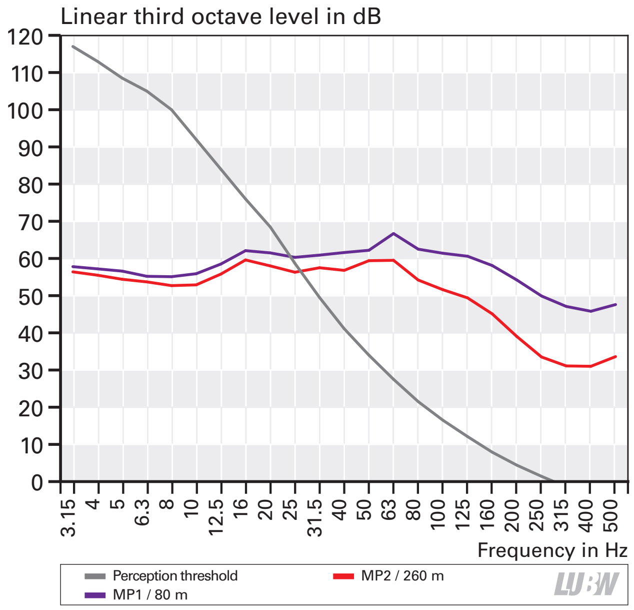
octave representation. The third octave levels in the infrasound range are at levels of around 60 dB and slightly below. In the low-frequency range, approximately between 40 Hz and 80 Hz, a slight peak can be seen. Here the measured values are significantly above the hearing threshold. The average traffic intensity is approximately 3,000 vehicles/h with a share of heavy-goods traffic of around 15 %. The G-weighted infrasound levels were around 75 dB(G) at a distance of 80 m and around 71 dB(G) at a distance of 260 m. Additional information concerning the G level can be found in Appendix A3.

5.4 Noise inside car while driving

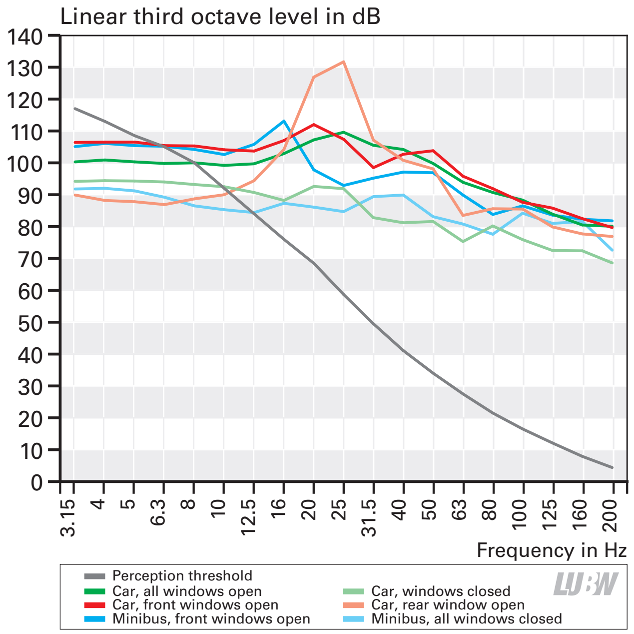
Below are the results of noise measurements carried out by the LUBW inside a moving car and a minibus on 06.09.2012. This is in fact no sound that occurs in the vicinity, i.e. no ambient noise or environmental noise in the strict sense. However, a lot of people are exposed to these sounds often and for longer periods of time, meaning that it surely makes sense to include such measurement values here. It became evident that relatively high levels in the infrasound range up to 20 Hz, as well as in the other low-frequency frequency range above 20 Hz occurred (**Firgure 5.4**, **Table 5.4**). It must be noted that, with windows open, the levels that arise in the area of low frequencies incl. infrasound are so high that they are subjectively perceived as being painful. The values measured by us correspond to the respective specifications in literature (e.g. [19] [20]).

5.5 Conclusion of the road traffic measurements

- It was possible to carry out the measurements for the low-frequency noise incl. infrasound resulting from road traffic without interfering wind noise. Unlike in the case of wind turbines, the recorded levels occur in the direct vicinity of residential buildings.
- As expected, it could be observed that the level of low-frequency noise including infrasound dropped at night. A good correlation with the traffic volume was also determined: The more the traffic, the higher the sound levels of low-frequency noise including infrasound.
- The Infrasound levels of traffic reach a maximum of 70 dB (unweighted) in individual thirds with respect to residential buildings in the vicinity. The G-weighted level



Firgure 5.3-2: *Frequency-dependent representation (linear third octave level) of a measurement at the motorway A5. As a comparison, the perception threshold according to Table A3-1 was also included. Note: The representation begins at a frequency of 3.15 Hz (in other illustrations partly from 1 Hz or 6.3 Hz). This is due to the measuring technology used.*



Firgure 5.4: *Low-frequency sound (averaging level) in the inside of car and minibus driving at approx. 130 km/h in comparison to the perception threshold according to Table A3-1*

***Table 5.4**: Infrasound level inside a passenger car or minibus while driving at 130 km/h*

Source	G-weighted level in dB(G)	Infrasound third octave level between 3.2 und 20 Hz in dB *
Interior noise in passenger car, all windows closed	105	88 to 94
Interior noise in passenger car, rear window open	139	87 to 127
Interior noise in minibus, all windows closed	100	85 to 93
Interior noise in minibus, side windows open	122	98 to 113

* Linear third octave level in dB(Z)

is in the range between 55 and 80 dB(G). This roughly corresponds to values found in literature for sea surf (***Table 2-1***).

- For road traffic, increased levels were detected in the frequency spectra in the range of between roughly 30 Hz and 80 Hz. Low-frequency noise in this area lies significantly above the hearing threshold and seems to be more relevant for an assessment than the infrasound level up to 20 Hz. The values in this low-frequency frequency range are significantly higher for the observed situations of road traffic than in the areas surrounding wind turbines (***Table 2-1***).
- The highest levels in the context of the measurement project were measured in the interior of a car travelling at 130 km/h. Even though these are not immission levels that occur in the free environment, they are an everyday situation that many people are frequently subjected to for a longer period of time. The measured values for both the infrasound as well as the other low-frequency areas are higher by several orders of magnitude than the values usually measured in road traffic or at wind turbines.

6 Urban background

The Friedrichsplatz in Karlsruhe was chose for the measurement of infrasound and low-frequency noise at day and night in an urban background. It is located in the heart of the city. The Friedrichsplatz is a rather quiet square located directly by the natural history museum. Benches, landscaped flower beds and a fountain invite passersby to linger and stop for a short break (***Figure 6-1***). The square extends for about 125 m from north to south and 100 m from east to west. The Erbprinzenstrasse crosses the Friedrichsplatz as a bicycle road. In a westerly and easterly direction are the Ritterstrasse and Lammstrasse respectively, with very slowly driving traffic. In the south, the square is limited by the natural history museum of Karlsruhe. To the west lies the Church of St. Stephan with forecourt. Apart from that, the Friedrichsplatz is surrounded by offices and commercial buildings, as well as a number of individual apartments. The next somewhat busier road is situated about 250 m to the south, shielded behind the natural history museum and the Nymphengarten (Kriegstrasse, B 10). Tram lines are located at a distance of several hundred metres, partially behind several blocks of buildings (***Figure 6-2***), and a construction site is located in a north-westerly direction.

The measurements were carried out simultaneously at three measurement points. The location of the measurement points is shown in the aerial view in ***Figure 6-3***. Measurement point MP1 was chosen in the inside of a building adjacent to the Friedrichsplatz (meeting room of the education authority of Karlsruhe). A second measurement point MP2 was placed on the ground of the Friedrichsplatz, a third measurement point MP3 on the roof of the museum of natural history (***Figures 6-4 to 6-6***). MP2 and MP3 were positioned on a reverberant plate.

The measurements were carried out from Friday, 20.09.2013, 3:00 p.m. to Saturday, 21.09.2013, 2:00 a.m. Preliminary

Figure 6-1: *Friedrichsplatz in Karlsruhe, looking south at the natural history museum. Photo: LUBW*

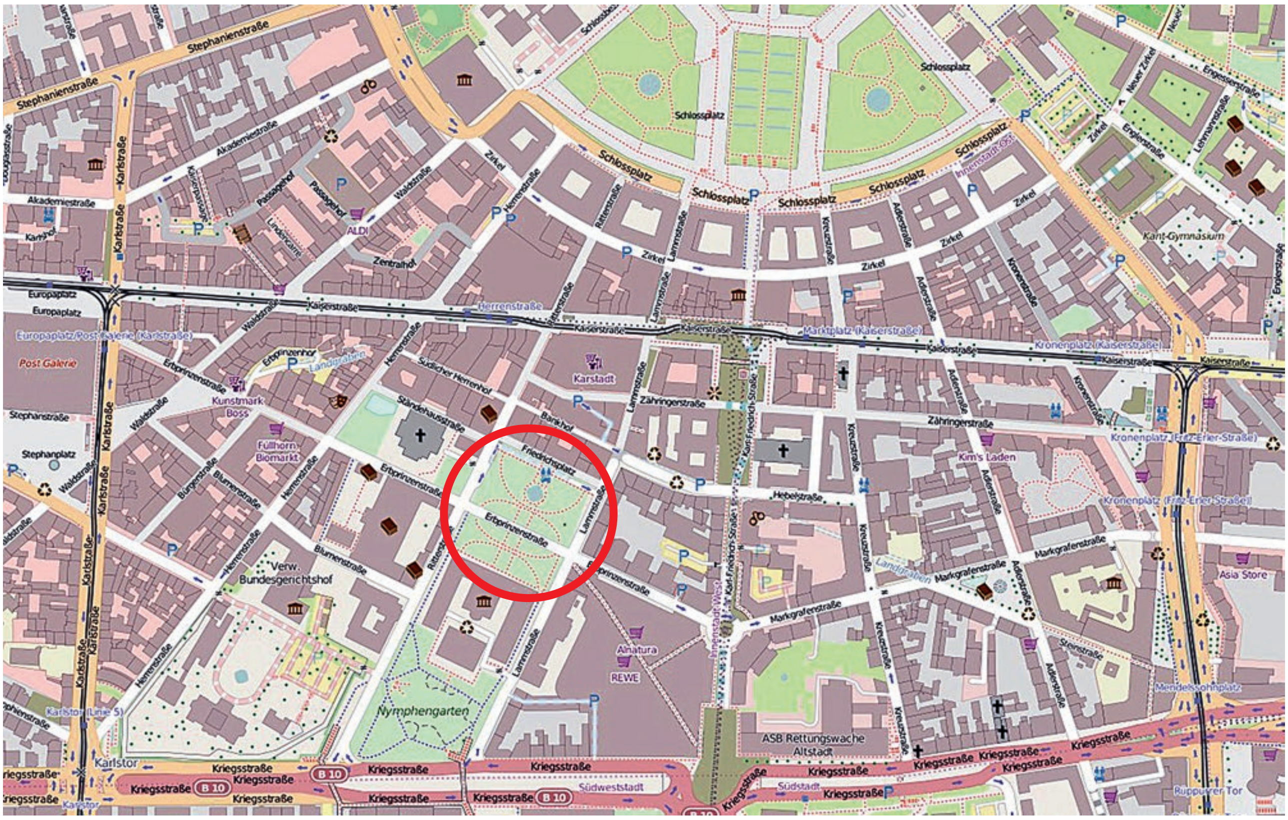


Figure 6-2: *City map of Karlsruhe with Friedrichsplatz (red circle) and the tram lines in the vicinity (dark and dashed lines). Source: www.OpenStreetMap.org*

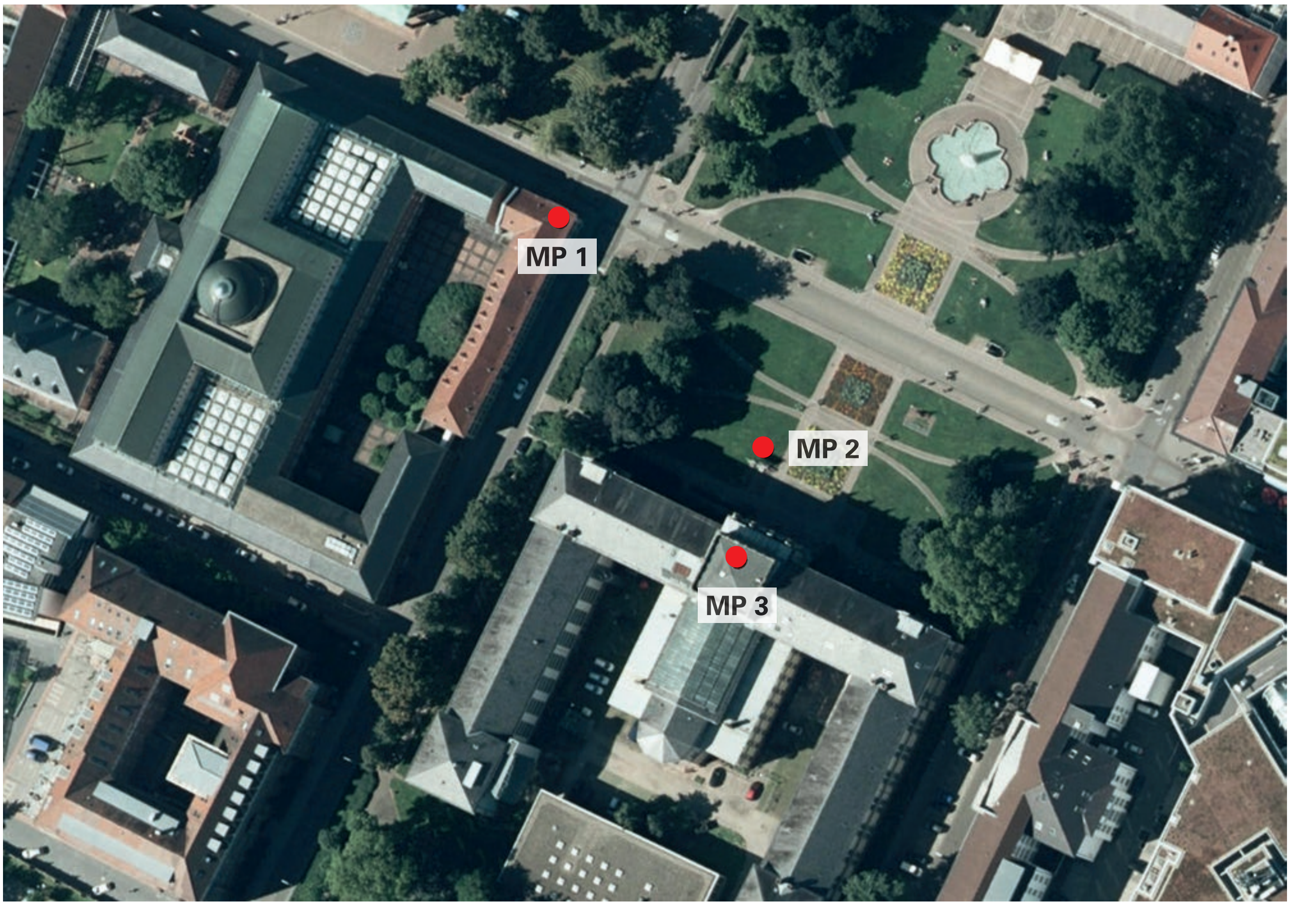


Figure 6-3: *Oriented aerial view of Karlsruhe Friedrichsplatz. Location of the three measurement points MP1 (meeting room of education authority), MP2 (on Friedrichsplatz) and MP3 (roof of museum of natural history). Source: LUBW, LGL*

measurements were taken by the LUBW on 26.06.2013. The measurements should enable conclusions to be made about the situation at day and at night. The volume of traffic (cars, pedestrians, cyclists) was typical for this site in the given weather conditions. In summer nights or during events, higher volumes will surely be the case.

Note: While the infrasound and low-frequency noise measured in the vicinity of operating wind turbines always contains a proportion of wind (and possibly also a share that is induced by the wind at the microphone), the conditions are much more favourable for the measurement of inner city noise. Here these effects related to the wind play virtually no role. The infrasound and low-frequency noise could be measured largely without any disturbing wind noise. Only on the roof of the museum of natural history did wind noise occur from time to time. For more information see page 73.

RESULTS

The measured third octave spectra for the three measurement points, each for the time periods 4:00 p.m. - 5:00 p.m., 10:00 p.m. - 11:00 p.m. and 12:00 a.m. - 1:00 a.m. are shown in ***Figure 6-8*** and are explained in the following:

At the measurement point MP1 (education authority, indoor measurement), third octave levels between just under 20 dB to 45 dB were measured in the infrasound area below 20 Hz. The values are all below the perception threshold. It is clearly visible that the infrasound levels drop at night by about 10 dB. In the further low frequency range a significant rise from 25 Hz to 63 Hz can be found, which is probably due to traffic noise and electrically powered equipment (the building was not without electrical power). All in all, the lowest levels are found at the indoor measurement at MP1 as a result of the absorption through the building envelope. The results of the indoor measurement were evaluated according to DIN 45680 (1997) [4],

Figure 6-4: *Setup of the measurement point MP1, indoor measurement at the education authority of Karlsruhe. Photo: LUBW*

Figure 6-5: *Measurement point MP2 on the Friedrichsplatz in front of the natural history museum Karlsruhe. Photo: LUBW*

Figure 6-6: *Microphone position at measurement point MP3 (roof of museum) with view over Karlsruhe. The meteorology was also determined at MP3. Photo: LUBW*

Figure 6-7: *View from measurement point MP3 (roof of museum) looking north over Karlsruhe. The floodlights of the KSC stadium in the Wildpark can be seen. Photo: LUBW*

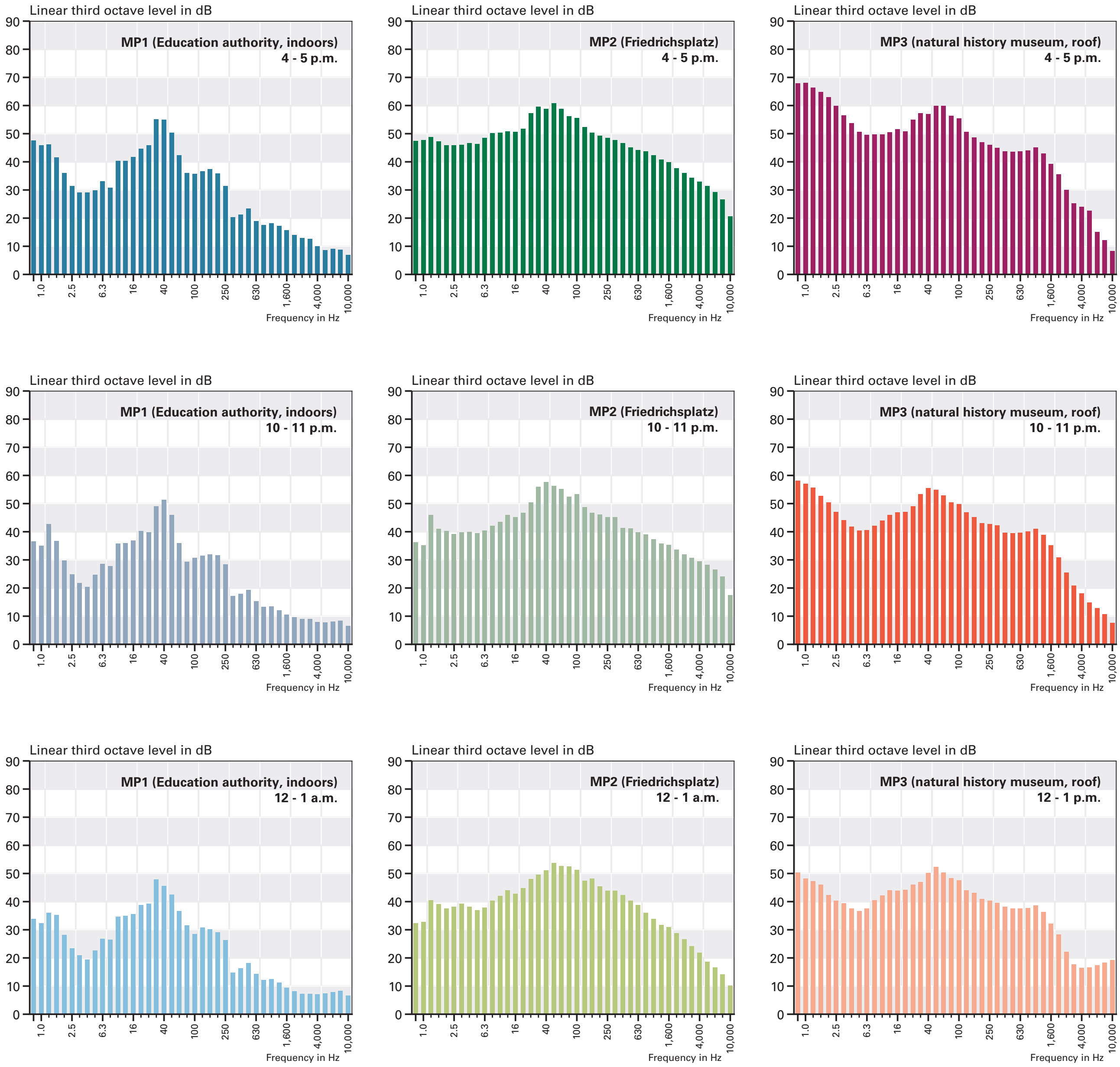


***Figure 6-8**: Measured third octave spectra for the three measurement points at different times of the day and at night. Left column: Measurement point MP1 (education authority, indoors); centre column: Measurement point MP2 (Friedrichsplatz); right column: Measurement point MP3 (natural history museum, roof). For explanations see text.*

even if the scope of this standard does not cover road traffic noise. Time periods with substantial influence of background noise at measurement point MP1 were excluded from the evaluation. The following periods of time were chosen: For the night period (10:00 p.m. - 11:00 p.m., loudest hour), as well as in accordance with the procedure of DIN 45680 (1997) [4] for the day period (4:00 p.m. - 5:00 p.m., loudest hour) as well as informatively for the night hour from 12:00 a.m. - 1:00 a.m. The reference values taken from the supplement sheet "Beiblatt 1" for above-stated norm (these are formally only valid for the operation of industrial plants) were exceeded in the daytime as well as night time periods. There were no clearly protruding single tones. For informative purposes, the measurement data was also evaluated according to the revised draft of DIN 45680 (2013) [5]. The reference values taken as a comparison (these are formally only valid for the operation of industrial plants) were exceeded in the daytime as well as night time periods.

The data of the measurement points MP2 and MP3 was respectively corrected according to Section 4.1 (reverberant plate). At the measurement point MP2 (Friedrichsplatz in front of the museum), third octave levels between

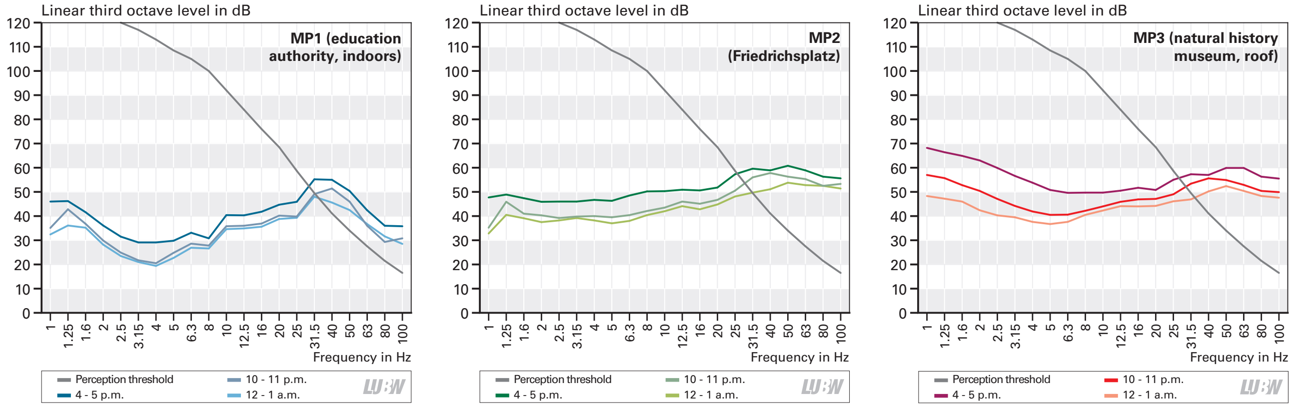


Figure 6-9*: Comparative frequency-dependent representation of the third octave sound level for the three measurement points at different times of the day and at night. The results for MP2 and MP3 have been corrected (reverberant plate, see Section 4.1). The perception threshold was also shown as a means of orientation. Left: measurement point MP1 (education authority, indoors); Centre: measurement point MP2 (Friedrichsplatz); right: measurement point MP3 (natural history museum, roof).*

just under 35 dB and a little over 50 dB were measured in the infrasound range up to 20 Hz. Here too, a decrease of the infrasound can be recognised later at night. In the low-frequency range, an excessive increase can also be seen, which can be attributed to the road traffic. This is where levels above 55 dB are also reached at night in the range of 32 Hz to 80 Hz, which is above the perception or hearing threshold. An interesting effect can be seen for the 1.25 Hz third, which, for example, clearly stands out in the third octave spectrum for MP2 between 10:00 p.m. and 11:00 p.m. This concerns a natural frequency of the Friedrichsplatz, which is largely surrounded by buildings (half a wavelength corresponds to merely the extent of the square). This effect can be analysed further in the narrow band spectrum (not shown here).

At the measurement point MP3 (museum roof), similar conditions as for MP2 can be seen – with two differences: For the infrasound below 5 Hz, an excessive increase can be seen, which here is attributed to the somewhat increased wind speed on the roof and the corresponding wind effects. An increase arising in the range above 500 Hz can at least partially be attributed to the rolling noises of cars on roads located further away, such as the B 10 (Kriegstrasse). These were noticeable on the roof, but were otherwise screened off. In the evening, it was possible to get a direct view of the KSC football club's Wildpark stadium, where a match was taking place (***Figure 6-7***).

In a further analysis of the narrow band spectra (not listed here), some individually protruding lines could be detected at some frequencies. However, these could not all be associated with specific sources.

In ***Figure 6-9*** the developments of the linear third octave levels in the range from 1 Hz to 100 Hz are presented for the measurement points MP1 to MP3 in comparison to the perception threshold (according to draft of DIN 45 680 [5]; below 8 Hz supplemented by literature values [11]). See also ***Table A3-1***. The results for MP2 and MP3 were corrected, as shown in Section 4.1, due to the use of a reverberant plate.

Figure 6-10 shows the course of the A-weighted and G-weighted sound level during the measurement at the measurement point MP2 (Friedrichsplatz). It can be clearly seen that the G level, which represents the low-frequency noise including infrasound, slowly and steadily decreases in the evening hours. The G levels at the measurement point MP1 (indoors) were mostly between 45 dB(G) and 60 dB(G) during the measuring period, and at times even above that. At the measurement points MP2 (Friedrichsplatz) and MP3 (roof), the values were mostly between 55 dB(G) and 65 dB(G), and partially reached levels above 70 dB(G).

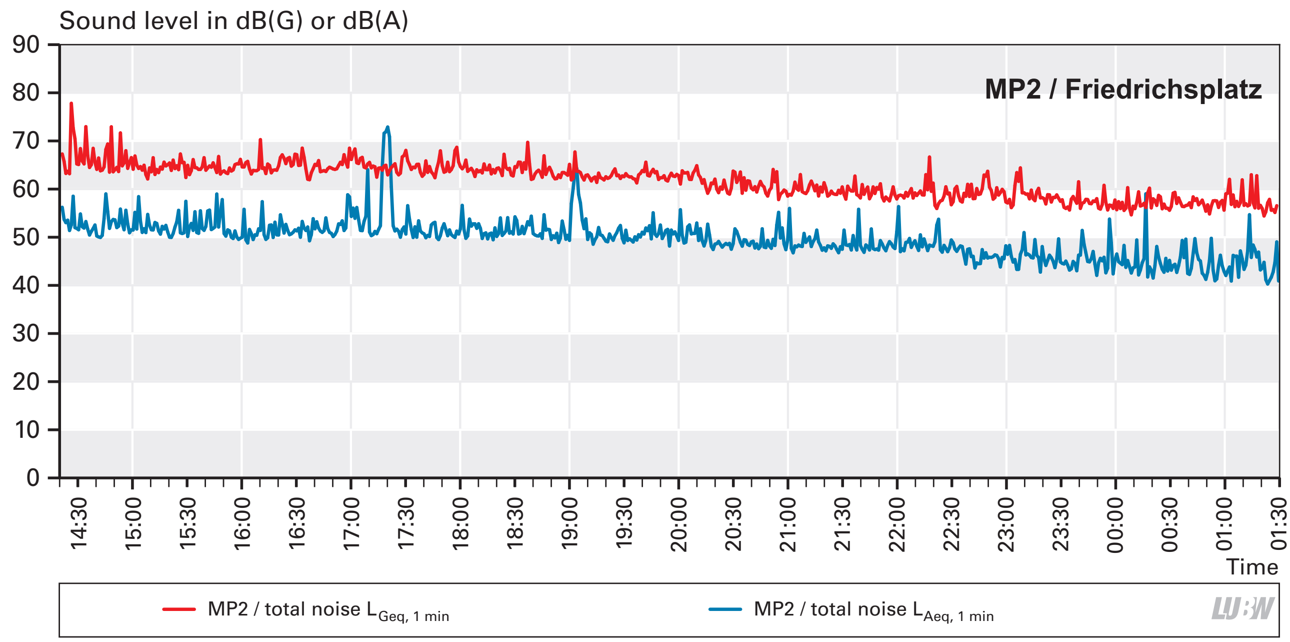


***Figure 6-10**: Course of the A and G-weighted sum level $L_{Aeq}(t)$ und $L_{Geq}(t)$ at the measurement point MP2 (Friedrichsplatz) in the time period 20.09.2013, approx. 2:30 p.m. to 21.09.2013, 1:30 a.m.*

7 Sources of noise in residential buildings

Life in the modern household is characterized by the use of technical devices, which are used to facilitate everyday life. The locations of the devices are normally chosen on the basis of the existing supply connections for electricity, water or gas. When doing so, people also generally pay attention to ensuring a preferably trouble-free use of the living quarters. Devices such as fridges or ventilation systems are permanently or intermittently in operation, while other devices such as vacuum cleaners or electronic tools are used only briefly. During operation, every technical device emits characteristic sounds. Depending on the source, different sound patterns can also be caused by different operating modes.

With the help of manufacturer‘s instructions, buyers can inform themselves about the expected noise levels prior to the acquisition of technical devices. However, the data sheets often only specify the A-weighted levels. These provide no indications of how the sound spreads across different frequencies.

In order to also be able to present low-frequency noise that may occur in a living environment in a comparative manner, the LUBW carried out sound level measurements in a residential building in the city centre of Tübingen. The apartment building in half-timbered construction style dates from the second half of the 19th century. The compartments of the walls are made of sandstone and the wood-beamed ceilings are filled with clay. The ceilings and walls are additionally covered with a 3-4 cm thick layer of lime plaster. In the course of renovation work during the last few years, the worksite sandstone slabs or tiles were moved onto a layer of reinforced cement screed in some areas, such as in the bathrooms. The building is located in a restricted traffic area; the next multilane roads are about 150 m away. Any traffic noise emanating from there is largely shielded by the building density of Tübingen city centre. The acoustic situation around the building is significantly characterized by the communication noise of passers-by.

The measurements on 04.08.2015 registered two washing machines from various manufacturers, one refrigerator, one oil heating and one gas heating. For detailed information on the used measuring instrumentation please refer to Appendix A4.

7.1 Washing machine

The washing machines were located in two apartments on the 1st and 2nd floor of the house. The measurements were each taken at a measurement point MP1 at close range within the room of the installation itself, as well as at a measurement point MP2 in a separate room. When measuring washing machine 1 on the 1st floor, the measurement point MP1 in the middle of the room was approx. 0.5 m from the washing machine. Measurement point MP2 was located approx. 3 m vertically above MP1 on the 2nd floor. Washing machine 2 was located on the 2nd floor. Here measurement point MP1 was also positioned in the middle of the room approx. 0.5 m from the washing machine, while measurement point MP2 in the adjoining room – separated by a wall – was positioned approx. 5 m away.

RESULTS

The measurements of the two washing machines took place in the period from 10:50 a.m. to 11:30 a.m. Periods with extraneous noise effects were excluded from the evaluation.

With washing machine 1 in operation, third octave levels between 44 dB and 76 dB in the infrasound range under 20 Hz were measured at measurement point MP1 (***Figure 7.1-1***). The highest levels occurred during the spin cycle and the lowest ones during the wash cycle. At measurement point MP2, third octave levels of 29 dB to 60 dB occurred below 20 Hz during the measurement of washing machine 1. Here, too, the higher levels were registered during the spin cycle.

At washing machine 2, the third octave levels at measurement point MP1 in the infrasound range below 20 Hz were between 35 dB and 70 dB (***Figure 7.1-2***). Here too, the highest third octave levels were registered in the spin cycle. The measurements at measurement point MP2 showed third octave levels between 26 dB and 71 dB in the same frequency range.

The curves for the individual modes of operation of the two measured washing machines are almost parallel for the measurement points MP1 and MP2 in the infrasound range below 20 Hz. In contrast, it can be seen that above 20 Hz the difference between the third octave levels measured at both measurement points increases with increasing frequency. This can be attributed to the sound insulation effect of the building components (ceiling or wall). The building components reduce the higher-frequency sound to a significantly higher degree than is the case in the infrasound range.

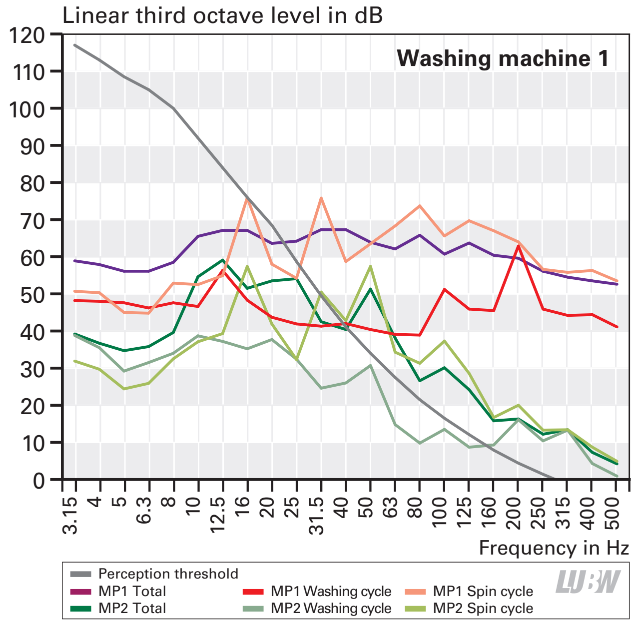


***Figure 7.1-1**: Third octave noise level of washing machine 1 at measurement points MP1 and MP2 for different operating states, with perception threshold according to Table A3-1 for comparison. "Total": Average level over the entire wash cycle.*

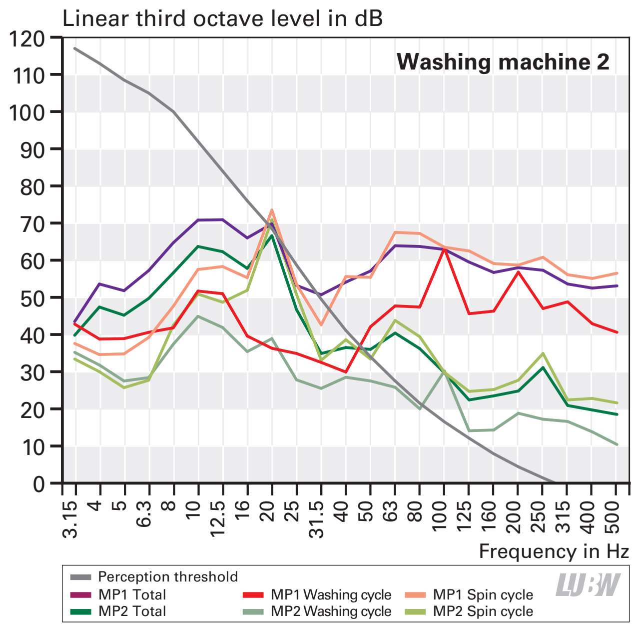


***Figure 7.1-2**: Third octave noise level of washing machine 2 at measurement points MP1 and MP2 for different operating states, with perception threshold according to Table A3-1 for comparison. "Total": Average level over the entire wash cycle.*

The single tone at 16 Hz (washing machine 1) as well as 20 Hz (washing machine 2) are caused by the respective rotational speed during the spin cycle. The 16 Hz third octave correlates with 960 rpm, the 20 Hz third octave with 1,200 rpm. The additionally emerging single tone at washing machine 1 at about 31.5 Hz is a harmonic overtone of the 16 Hz third octave. Depending on the operating mode, single third octave levels can reach the perception threshold according to ***Table A3-1*** between roughly 16 Hz and 20 Hz; above 50 Hz the third octave levels are generally in the audible range.

7.2 Heating and refrigerator

The two heating units measured were an oil boiler in the basement with pressurised atomiser burner on the one hand, and a gas water heater installed on a wall in the bathroom of the 2nd floor on the other. The fridge was located on the 2nd floor in a corner of the kitchen. The measurements of these noise sources were each carried out at a measurement point at a distance of about 0.5 m.

RESULTS

The third octave spectra during operation of the two heating systems as well as the refrigerator in the period from 11:40 a.m. to 1:30 p.m. were measured using technical measuring equipment. The results of the measurements are shown in ***Figure 7.2-1***. As was the case for the other measurements, extraneous noise, e.g. caused by measuring staff or passers-by outside, was excluded from the assessment.

Levels of approx. 55 dB to 70 dB were measured at the oil heating in the infrasound range below the 20 Hz third octave. In the low-frequency range between 20 Hz and 80 Hz, the third octave levels are between 55 dB and 60 dB. A single tone with a third level of 74 dB is recognisable at 100 Hz. Levels between 40 dB and 50 dB were measured at the gas water heater in the infrasound range below 20 Hz. In the low-frequency range between 20 Hz and 80 Hz, the third octave levels measured at the gas heating are between 40 dB and 50 dB. The difference between the levels measured at the oil heating and the gas water heater in the low-frequency range is between 10 dB and 40 dB.

The fridge measured in the kitchen of the 2nd floor delivered third octave levels of between 32 dB and 50 dB in the infrasound range. Third octave levels between 17 dB and 50 dB were measured at the refrigerator between 20 Hz and 80 Hz. While the third octave spectrum of the oil heating clearly sets itself apart from the other measured units through higher levels, the third octave spectra of the gas water heater and the refrigerator are very similar.

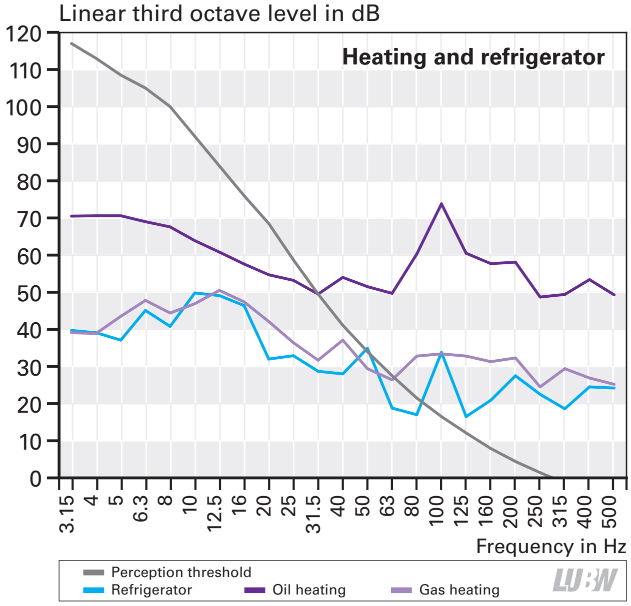


***Figure 7.2-1**: Third octave sound level of the noise from oil heating, gas heating and refrigerator at a distance of 0.5 m from the unit, with perception threshold according to Table A3-1 for comparison*

SUMMARY

During the measurements in the residential building, the highest levels at washing machines were recorded during the spin cycle. Tonalities in individual third octaves correlate with the rotational speed of the drum of the washing machine during the spin cycle. As expected, building components dampen higher frequency noise components more than at low frequencies. The perceptual threshold according to ***Table A3-1*** was reached for the washing machines in the frequency range above 16 Hz and 20 Hz respectively. With the other devices, the infrasound level did not reach this threshold.

8 Natural sources

8.1 Rural environment

In order to make statements about how much infrasound is caused by wind in the great outdoors, sound level measurements were carried out within the framework of the measuring programme on 09.05.2015 with strong winds in an open field (measurement point MP1), on the edge of a forest (measurement point MP2) and in a forest (measurement point MP3). The three points were aligned downwind of each other, starting with MP1. As with the wind power plants, the sound level measurements were carried out on a reverberant plate with a primary and secondary wind screen. At the same time, the wind speed was measured at 10 m height (open field) at the measurement point MP1. ***Figures 8.1-1 to 8.1-3*** provide an impression of the positioning of the measurement points. The measurement point MP1 lies approx. 130 m from the edge of forest.

The evaluation was carried out for the frequency range between 1 Hz and 10 kHz. The procedure corresponded to the analysis of the measurements at wind power plants, as described in Section 4. Two time periods were examined per measurement point at different wind speeds (6 m/s and 10 m/s at the measurement point MP1, open field), within which the wind blew evenly if possible. As a result, two situations with widely differing environmental conditions were recorded. Due to the spatial situation at the measurement points MP2 (edge of forest) and MP3 (forest) it can be assumed that at the same given point in time the wind speed is lower there than at the measurement point MP1 (open field).

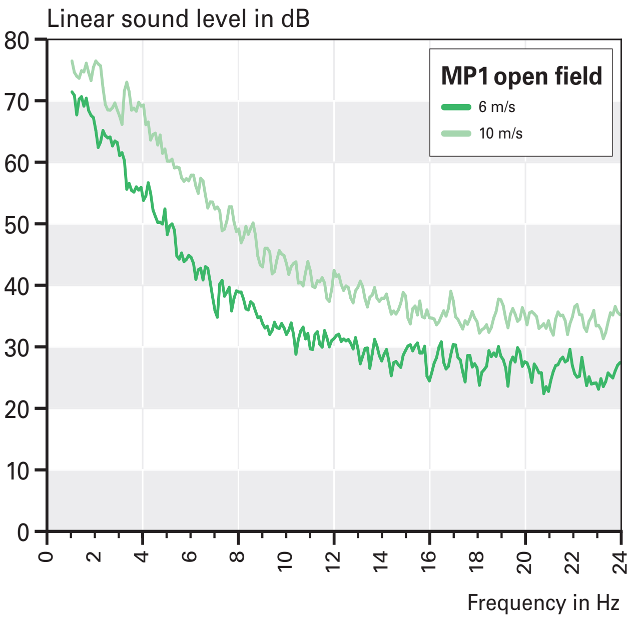
RESULTS: NARROW BAND LEVEL

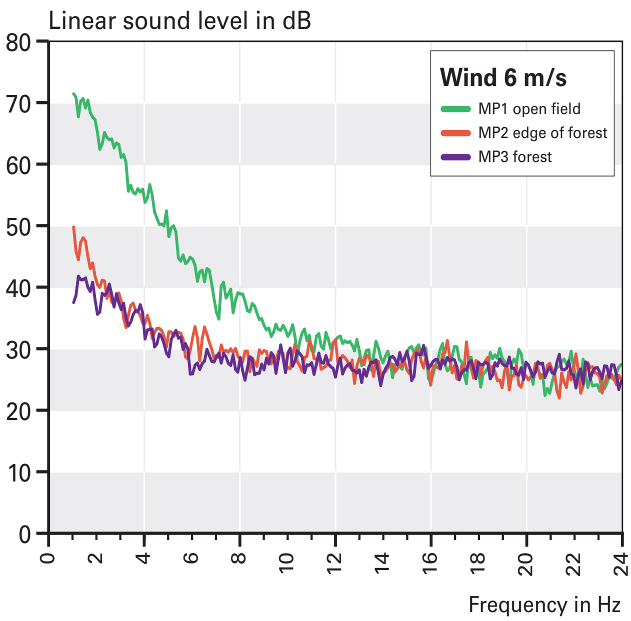
Figure 8.1-4 shows the narrow-band spectra determined from the audio signals at an average wind speed of approx. 6 m/s and 10 m/s at a height of 10 m (measured at the measurement point MP1). The three charts in the left column enable a comparison of measurement results for the two wind speeds at each measurement point. The two graphs in the right column show the sound levels that were recorded at the three measurement points for each of the wind speeds 6 m/s and 10 m/s. It can be seen clearly how the le-

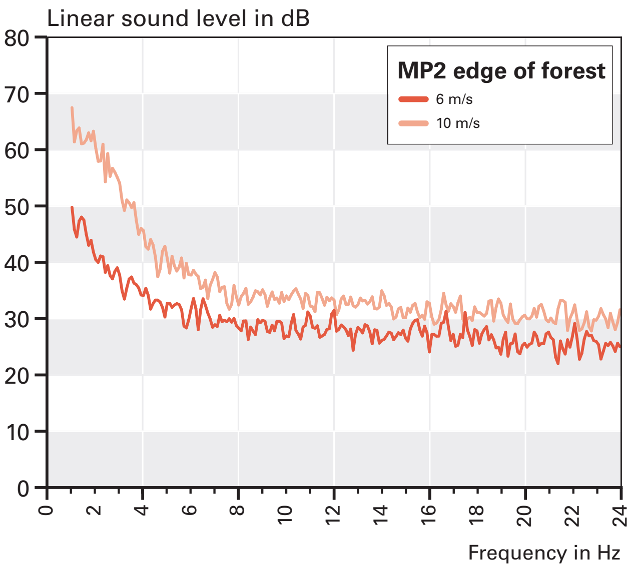
Figure 8.1-1*: Measurement point MP1 on open field (left) and meteorology mast (right), looking in direction of forest. Photo: Wölfel company*

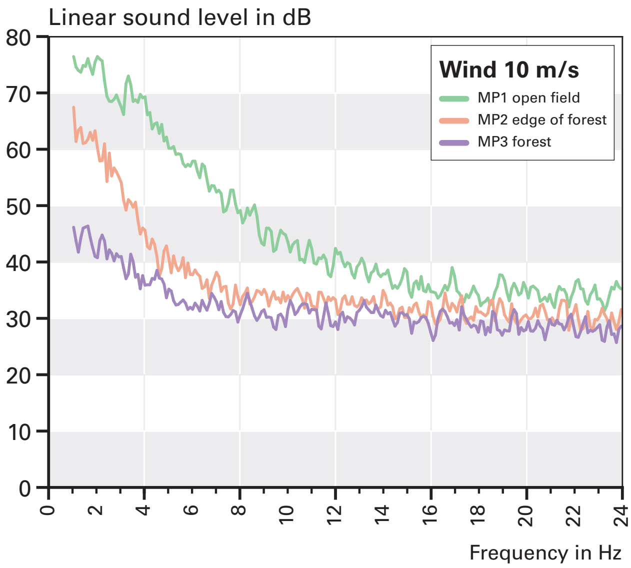
Figure 8.1-2*: Measurement point MP2, edge of the forest. Photo: Wölfel company*

Figure 8.1-3*: Measurement point MP3 in the forest, approx. 90 m from measurement point MP2. Photo: Wölfel company*









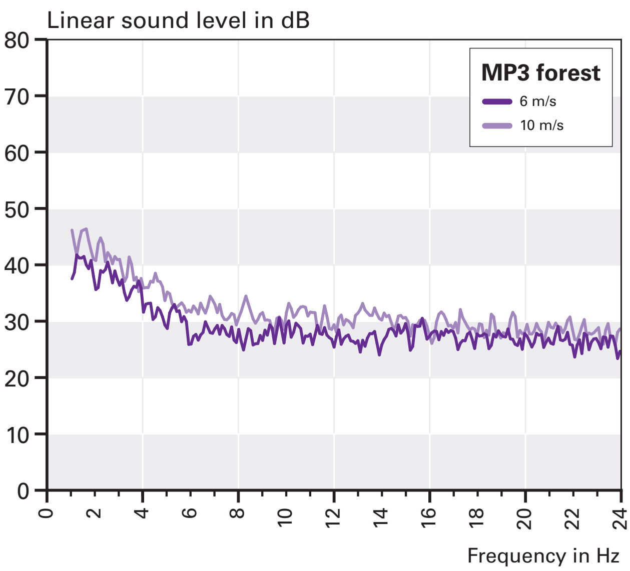


***Figure 8.1-4**: Narrow band spectra of noise at the measurement point MP1 (open field), MP2 (edge of forest) and MP3 (forest) for the frequency range of infrasound at different wind speeds. The wind measurement was always carried out at the measurement point MP1 (open field).*

Left column: Comparison of narrow band levels for the various wind speeds, separately presented for the measurement points MP1 (open field), MP2 (edge of forest) and MP3 (forest).

Right column: Comparison of the narrow band level at the three measurement points, represented separately for the wind speed 6 m/s (above) and 10 m/s (below)

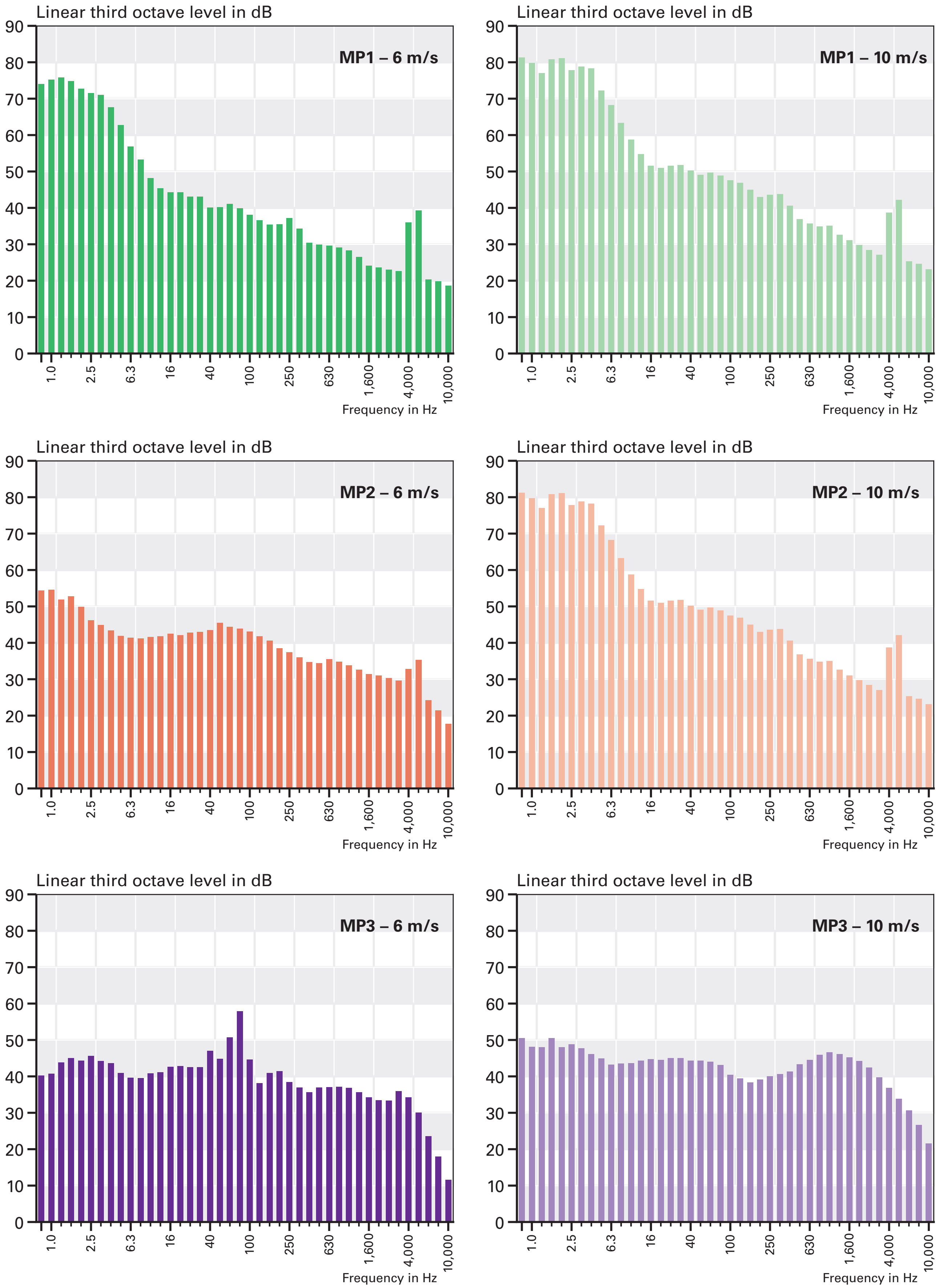


Figure 8.1-5*: Third octave spectra of the background noise at the measurement point MP1 (open field), MP2 (edge of forest), and MP3 (forest). Left column: Wind speed 6 m/s; right column: Wind speed 10 m/s. The wind measurement was always carried out at the measurement point MP1 (open field).*

vels depend on the measuring position and the wind speed. On an open field, the levels are about 10 to 15 dB higher at a wind speed of 10 m/s than at a wind speed of 6 m/s. At the edge of the forest, this difference is somewhat weaker for frequencies above roughly 5 Hz. The difference is only 5 to 10 dB. In the forest, the difference is 5 dB or less. The spread of the measured values between the three measurement points falls from roughly 30 dB at the lowest end of the spectrum to 0 to 5 dB at the upper end, depending on the wind speed. Noteworthy level differences between the edge of the forest and the forest occur only below 10 Hz. The differences in level between open field and forest, on the other hand, become less only above 20 Hz.

RESULTS: THIRD OCTAVE LEVEL

The third octave spectra of the background noise at all three measurement points for the frequency range from 0.8 Hz to 10,000 Hz are presented in ***Figure 8.1-5***. The wind speed was 6 m/s (left column) and 10 m/s (right column). On the open field, the low frequencies are predominant in the spectrum; at the edge of the forest and even more so in the forest, however, a shift to higher frequencies can be seen. While the wind becomes less the closer it gets to the forest, and less wind noise is therefore induced at the microphone, the noise from the leaves in the forest increases considerably. The peak values at about 4,000 Hz are due to the chirring of crickets and chirping of birds.

COMPARISON WITH THE PERCEPTION THRESHOLD

Figure 8.1-6 shows the third octave spectra of the total noise at the measurement points field, edge of forest and forest for the frequency range from 1 Hz to 100 Hz along with the perception threshold for comparison. The wind speed was 10 m/s. In the range of infrasound, the curves are well below the perception threshold.

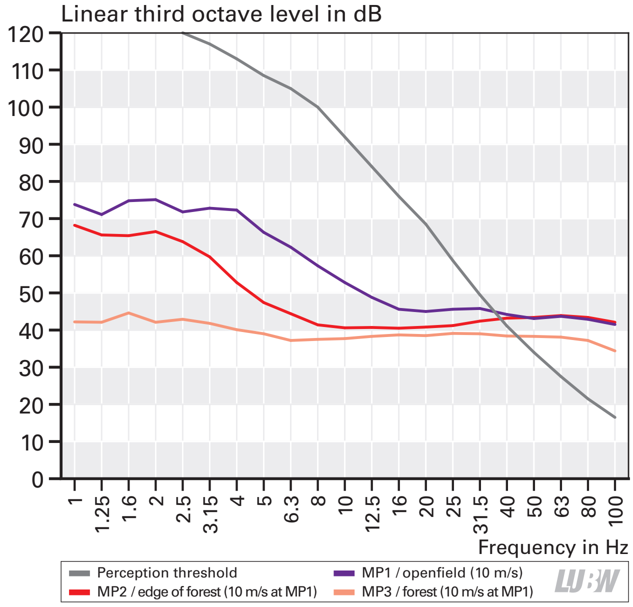


Figure 8.1-6: *Comparison of the third octave spectra of the total noise at the measurement points MP1 (open field), MP2 (edge of forest) and MP3 (forest) with the perception threshold according to Table A3-1. The measured values were corrected in accordance with Section 4.1.*

INFLUENCE OF WIND SPEED

The data in ***Figure 8.1-7*** shows that both the audible sound level (A level) and the infrasound level (G level) increase with increasing wind speed. Worth noting is the decrease in level of the G-weighted level from the measurement point MP1 (open field) in the direction of the measurement point MP3 (forest). This correlates with the decreasing wind speed when moving from the open field towards the forest. Wind-induced effects on the microphone can be generally ruled out (see Section 4.5 and 4.6, measurement in hole in the ground). The A-weighted level increases the closer you get to the forest, which can be attributed to the rustling of leaves, which is reflected in the A level.

Table 8.1-1: *Infra sound in a rural location at the three measurement points at different wind speeds*

Measurement point	G-weighted level in dB(G) Wind 6 / 10 m/s	Infrasound third octave level ≤ 20 Hz in dB * Wind 6 / 10 m/s
MP1 open field, 130 m from forest	50-65 / 55-65	40-70 / 45-75
MP2 edge of forest	50-60 / 50-60	35-50 / 45-75
MP3 forest	50-60 / 50-60	35-40 / 40-45

* Linear third octave level in dB(Z)

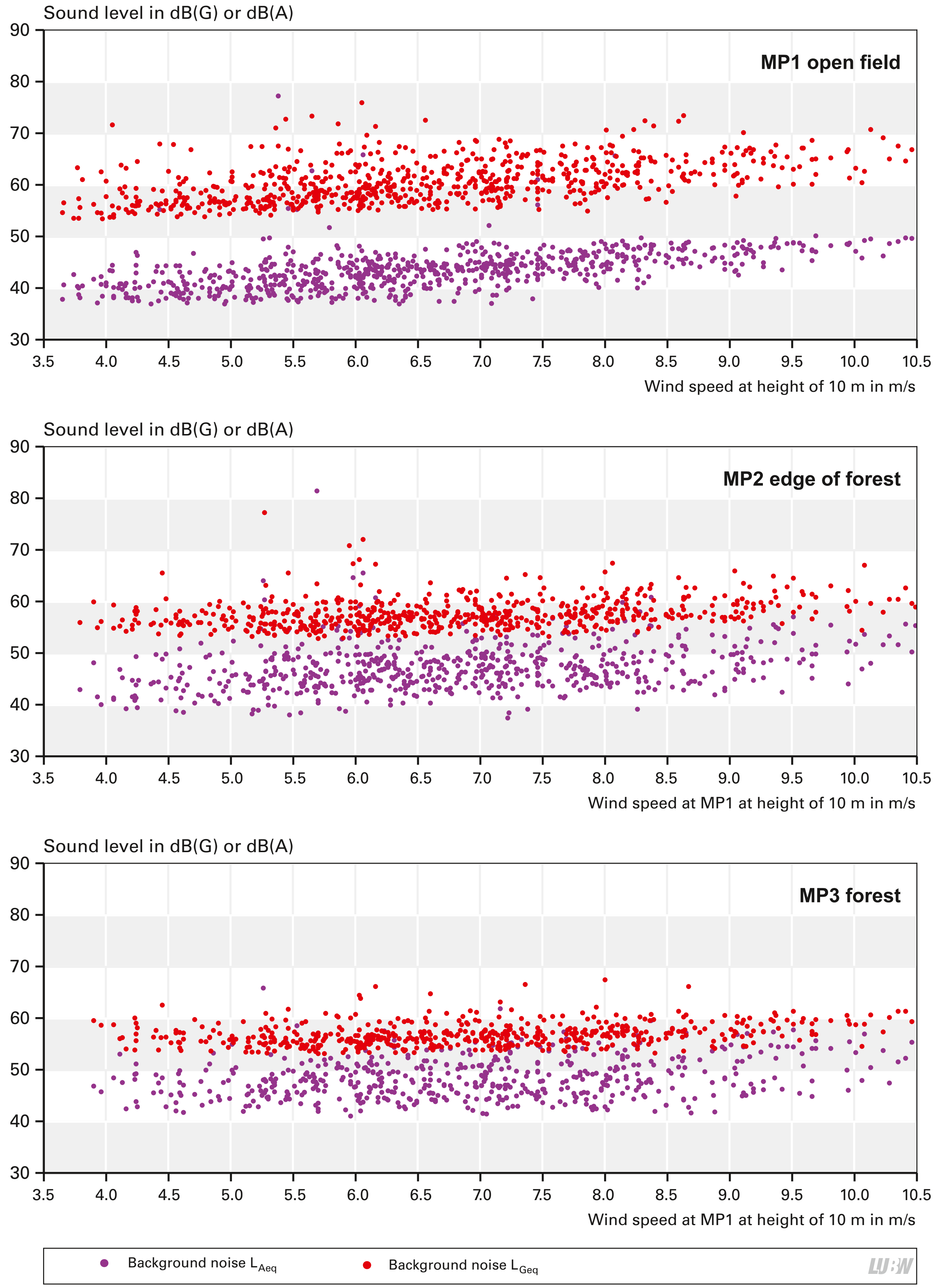


***Figure 8.1-7**: Audible sound level (A level) and infrasound level (G level) depending on the wind speed for the three measurement points MP1 (open field), MP2 (edge of forest) and MP3 (forest). The G levels (red dots) and the A levels (violet dots) are shown. The wind measurement was always carried out at the measurement point MP1 (open field).*

CONCLUSION

The infrasound shows a strong dependence on the measuring position. The linear levels in the narrow-band spectrum measured in the open field were up to 30 dB higher than the levels measured in the forest (***Table 8.1-1***). The differences are not as pronounced above 16 Hz, but a tendency towards higher levels can be seen in the open field compared to the forest at low frequencies. Higher levels were measured for A-weighted audible sound in the forest, which is attributable to the rustling of leaves.

8.2 Sea surf

In addition to wind noise, sea surf is a widespread natural source of low-frequency noise and infrasound. The LUBW was not able to take its own measurements at the coast within the framework of this project. Therefore, currently published values shall be drawn upon in order to provide an order of magnitude. In 2012 Turnbull, Turner and Walsh published metrics for sea surf as a natural source of infrasound [21]. Accordingly, the G-weighted infrasound level on a beach was 75 dB(G) at a distance of 25 m from the waterline, 69 dB(G) at a distance of 250 m from a cliff, and 57 dB(G) at a distance of 8 km from the coast (***Table 8.2-1***). Near the coast, the third octave levels at different frequencies below 20 Hz were in the range of 53 dB to 70 dB (***Figure 8.2-1***).

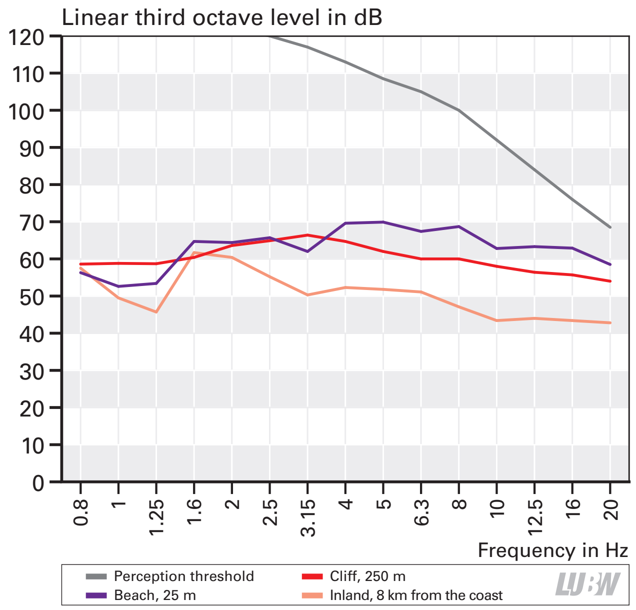


Figure 8.2-1: *Third octave spectra of the total noise of surf, different boundary conditions according to [21], perception threshold according to Table A3-1 for comparison*

Table 8.2-1: *Infrasound levels of sea surf for different boundary conditions*

Source	G-weighted level in dB(G)	Infrasound third octave level ≤ 20 Hz in dB *
Beach, 25 m from the waterline	75	53 to 70
Cliff, at distance of 250 m	69	54 to 65
Inland, 8 km from the coast	57	43 to 63

* Linear third octave level in dB(Z)

9 Design of a long-term measuring station for low-frequency noise

9.1 Task

An integral part of the measurement project "Low-frequency noise incl. infrasound from wind turbines and other sources" was the setup of a feasibility concept for a self-sufficient long-term measuring station with which to measure and document the noise situation at wind turbines. In particular, low-frequency effects were to be taken into account. When designing the concept, it was assumed that such a measuring station is to be used primarily in the context of monitoring measurements or in connection with complaint cases. Furthermore, the long-term measuring station should also provide a possibility to carry out special studies, e.g. for the determination of infrasound or sound modulations or before/after analyses. The following specifications had to be taken into account:

- DIN EN 61400-11 "Windenergieanlagen – Teil 11: Schallmessverfahren" (2013) [6]
- Technical guidelines for wind turbines, part 1, revision 18 (as of 01.02.2008, issued by FGW Fördergesellschaft Windenergie e.V.) [7]
- Technical instructions on noise abatement – "TA Lärm" (1998) [10]
- DIN 45680 "Messung von Bewertung tieffrequenter Geräuscheinwirkungen in der Nachbarschaft" (1997) [4] as well as DIN 45680 "Messung und Beurteilung tieffrequenter Geräuschimmissionen" (2013 draft) [5].

In addition, a mains voltage-independent operation of the measuring station should be ensured for a period of two to four weeks.

9.2 Concept

The design of the measuring station was to include in particular the technical equipment, the evaluation of the measured data as well as the evaluation of the results in the context of immission protection. In principle, the projected long-term measuring station is divided into the following functional modules:

- Unit for detecting the operating parameters of the wind turbine
- Meteorology measuring unit
- Noise measuring unit
- Device monitoring (remote control unit)
- Data centre (database and data analysis)

If the task requires it, the long-term measuring station could contain several similar measurement units. The basic design of a possible long-term measuring station is shown in ***Figure 9.2-1*** dargestellt.

9.3 Individual modules for data acquisition

FACILITY AND OPERATING PARAMETERS

Approximate statements regarding the operating state of a wind power plant can be derived from wind data determined near the measuring location. However, this does not apply for special operating modes of the system (e.g. low noise operation, system downtime in case of insufficient wind conditions).

Reliable results for the current performance of a wind turbine require the continuous determination of the actual turbine and operating parameters such as system power, rotor speed, nacelle angle, blade angle, wind speed and wind direction. Typically, the system operator already records these parameters as part of standard procedure. However, taking over such data from the operator into the collective of the data determined by the long-term measuring station is often difficult, if not impossible, in practice. It is therefore much more reliable, yet more bothersome, to record the turbine operation data on one's own measuring system. In order to do so, the turbine signals would have to be decoupled from the turbine control system of the wind

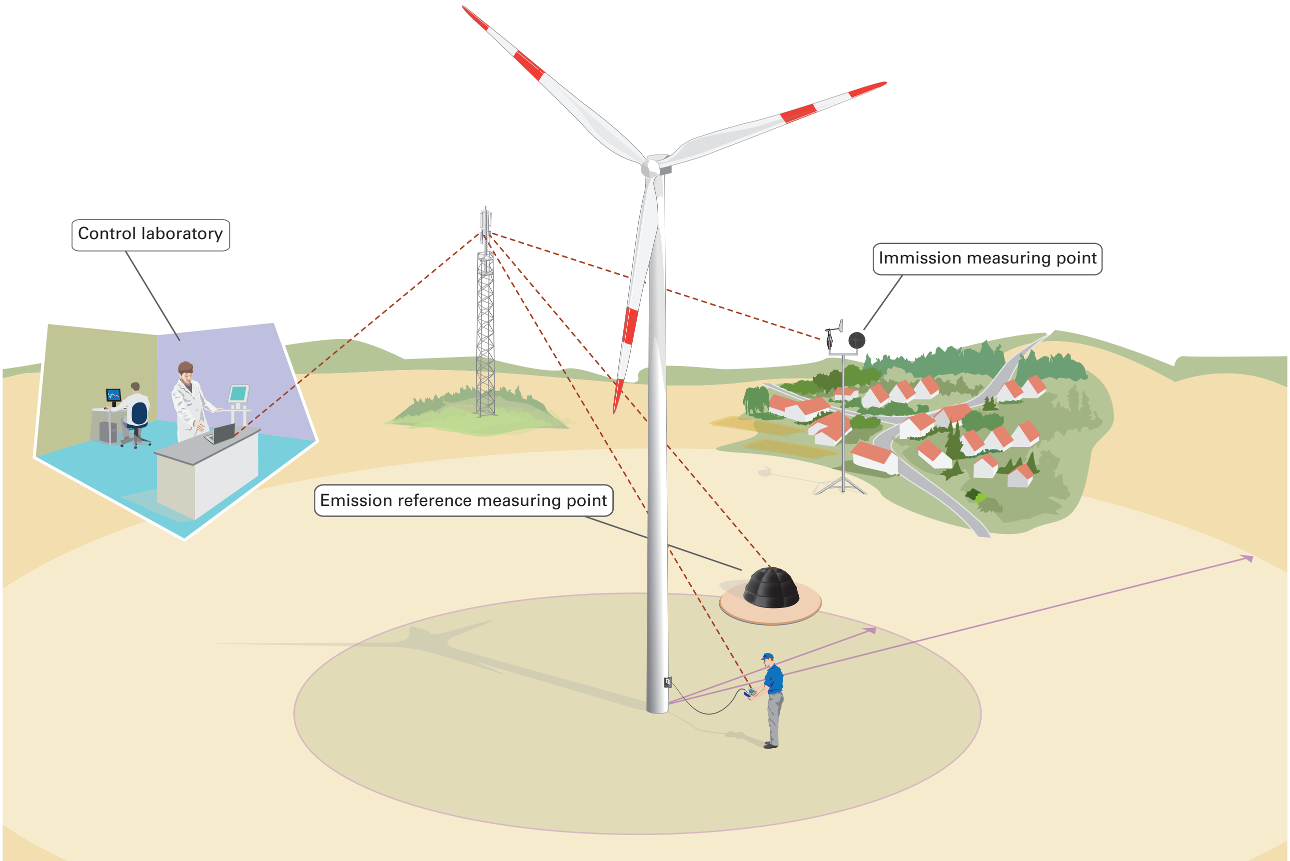


Figure 9.2-1*: Basic design of a possible long-term monitoring station*

power plant via transducers or existing interfaces, and be registered by the appropriate data loggers. With this type of gathering of data, the data recording (sampling sequence, data formats, etc.) can be devised according to its own standard. Thus, optimal data integration into the overall system would be guaranteed. However, this would certainly require the support by trained personnel during the setup and connection of the measuring system to the turbine control.

WEATHER DATA

In addition to the noise measurement data, the meteorological variables – mean wind speed, mean wind direction (each in 10 s intervals) – as well as precipitation, air temperature and air pressure have to be determined. Commercially available weather stations (sensors and data loggers) equipped with sufficient data storage could be used for this purpose. The collected meteorological parameters are then linked with the other metrics in the data centre. If technically possible, the recording of meteorological data could already be carried out on location together with the noise measurement data in the sound level analyser. The wind data should be collected at a height of up to 10 m above ground. The respective masts that can also be used on rough terrain are provided by a number of manufacturers.

ACOUSTIC DATA

In order to measure the acoustic data, a combination of devices consisting of a standard sound level analyser and changeable microphone unit can be used. As far as necessary or appropriate, further functional units such as controller, monitoring system or meteorology recording can be included or attached. The noise measuring system is fundamentally suitable for determining emissions (DIN EN 61400-11 [6]), noise immissions (TA Lärm [10]) and low-frequency noise (DIN 45680 [4]). The following specifications must be met by the sound level analyser:

- Calibratable sound level meter according to DIN EN 61672-1:2003 [22] Class 1, with standard microphone and third octave filters according to DIN EN 61260:2003 [23] Class 1

- Usable range of levels: 18 dB(A) to 110 dB(A), usable frequency range: 1 Hz to 20 kHz
- Ongoing collection of different sound levels (L_{Aeq}, L_{AFmax}, L_{Ceq}, L_{CFmax}, $L_{TerzAeq}$, $L_{TerzAFmax}$) in periodic times of 0.1 s to 10 s
- Continuous recording of the audio signal and hourly storage as a WAV file. The data storage capacity must be sufficient for records of at least two weeks, or in the case of a restricted frequency range of the audio recording for recordings of at least four weeks
- Extensive trigger management (timed triggering and external trigger option)
- Alternatively usable infrasound microphone (lower limiting frequency ≤ 1 Hz, uncertainty at 1 Hz ≤ ± 3 dB)
- Additional weatherproof microphone plate with primary and secondary wind screens according to DIN EN 61400-11 [6]
- Additional primary and secondary wind screens for mounting on tripod or measuring mast for immission measurements according to TA Lärm [10]

DEVICE MONITORING

Ideally, the possibility should be given to monitor and control all measuring systems wirelessly via an Ethernet or GSM connection from the data centre. If permitted by the data connection, a transfer of the stored data to the data centre should also be possible.

In order to increase the transparency of the respective measuring project, a real-time display of measurement results on a publicly accessible website could also be enabled.

GENERAL REQUIREMENTS

In general, it must be possible to operate all devices of the long-term measuring station with 12 V direct voltage independently from the public power supply network. The measuring station should be equipped with the respective power supply units. A maintenance-free continuous operation of four weeks ought to be ensured. The long-term measuring station should generally be designed in a weatherproof manner. As far as necessary, all parts should be sufficiently protected from the weather (precipitation, sun, wind). Operation in an air temperature range of -5 °C to +30 °C must be made possible. The long-term measuring station must be fitted with safety features against damage by animals, against vandalism and against theft.

9.4 Central data evaluation

The evaluation of the data gathered on location and its compilation to measurement reports is generally carried out in the data centre after the end of the measurements. The nature and scope of the evaluation depends on the predefined task. The actual data evaluation can largely be carried out automatically. Analysis programmes for this purpose are commercially available. The following points should be considered for the evaluation:

- Data preparation: Individual data that is required but cannot be determined on location can be derived from the measured data or the audio recordings. (e.g. G-weighted noise levels, narrowband frequency analyses, tonalities, impulsiveness).
- Data synchronization: The individual values of the turbine data, the meteorological measurements and the acoustic measurements are to be consolidated for the same period lengths (e.g. 10 s) and to be synchronised to the same absolute points in time.
- Rectifying faults: If there is extraneous noise at the measurement point as well as noise from the wind power plant, this could lead to misinterpretations of the noise situation. The levels of the noise influenced by extraneous sources therefore must be excluded when determining the turbine noise levels. This requires a comprehensive plausibility check of all measured data for every individual case. Impulsive background noise can often be well recognized from the level curve, ongoing external noise interference can often be seen only on the basis of the level curves of individual frequency bands. When in doubt, the audio recordings will have to be referred to.

9.5 Applicability and benefits

The affected population is often rather sceptical when it comes to projected noise levels or measurements of wind turbines that are taken within a matter of hours. It is thus that the people affected often assume that the applied procedures do not take into account all facets of possible disturbances. Also, it is believed that the worst operating mode of the wind turbine is often not the basis for the noise measurements. In such cases, the use of a long-term measuring station is a good idea. In order to increase its acceptance, the general population could also be involved in the evaluation proceedings.

FIELDS OF APPLICATION

- Determination of the noise emissions and immissions caused by wind power plants subject to wind and plant operating conditions. Generation of different statistics on noise occurrence, plant parameters or wind conditions.
- Comparison of the results with the reference values and indicators in the TA Lärm and DIN 45680 [4, 5], as well as the level values used or specified in the approval procedure.
- Determination of the infrasound influencing a measurement point, possibly depending on the wind and plant operating conditions.
- Determination of noise exposure at a location before and after commissioning of wind turbines.
- Identification of specific or not regularly occurring noise or sound effects, for example implemented by complainants.
- Ultimately, the operation of such a long-term measuring station could be seen as a contribution towards the protection of the population against the harmful effects of noise, and in particular as a contribution to the pacification of the conflict situation on location.
- The use of a long-term measuring station is not suited as a means of carrying out acceptance tests. Such measurements require direct support through expert staff.

Appendix A1 – General information

The following sections provide information on infrasound and low-frequency noise in generally understandable form. This concerns the development, occurrence, spreading as well as the evaluation and perception of infrasound and low-frequency sound [15] [19] [24] [25] [26] [27] [28].

A1.1 LOW-FREQUENCY NOISE AND INFRASOUND

Put simply, sound consists of compressional waves. When such pressure fluctuations spread in the air, one refers to them as airborne noise. A human's sense of hearing is able to capture sound, the frequency (see Appendix A3) of which lies between approximately 20 Hz and 16,000 Hz (for children this value is about 20,000 Hz). Low frequencies correspond to low notes while high frequencies correspond to high notes. Sound below the audible range, i.e. with frequencies below 20 Hz, is called infrasound. Noise above the audible range, i.e. with frequencies above 20,000 Hz, is known as ultrasound. Low-frequency noise is defined as sound which is primarily within the frequency range below 100 Hz. Infrasound is thus a part of low-frequency sound.

Periodic air pressure fluctuations spread with a velocity of approximately 340 meters per second. Low-frequency vibrations have large wave lengths while high-frequency vibrations have small wave lengths. For example, the wavelength of a 20 Hz tone in air is about 17 m, while a frequency of 20,000 Hz has a wavelength of 1.7 cm (see ***Table A1-1***).

A1.2 SOUND PROPAGATION

The propagation of infrasound and low-frequency sound follows according to the same physical laws as all kinds of air-borne noise. A single sound source, such as a wind turbine generator, emits waves that spread in all directions in a spherical manner (***Figure A1-1***). As the sound energy is distributed across an ever growing area, the noise intensity decreases per square meter in an inverse proportion: With increasing distance it quickly becomes quieter (roughly 6 dB per doubling of distance). In addition, there is also the effect of absorption of sound through the air. A small part of the sound energy is converted into heat during the spread of the waves, resulting in additional absorption. This air absorption depends on the frequency: Low-frequency sound is only slightly absorbed while high-frequency is absorbed more. In comparison, the decrease of the sound level over distance significantly outweighs the decrease through air absorption. When spreading across flat surfaces, interference can occur, leading to highly fluctuating sound levels. A pressure build-up may occur in front of large obstacles leading to an increase in the sound pressure level. Standing waves may occur outdoors between the facades of buildings. Furthermore, a special feature of low-frequency sound waves is their low absorption through walls or windows, meaning that effects can also occur inside of buildings. Here too, the formation of standing waves may be the case. However, in the infrasound range these can arise only in large halls or churches; in common residential buildings the fundamental oscillations are at higher frequencies.

Table A1-1: *Relationship between frequency and wavelength for sound waves in the air*

Frequency	1 Hz	10 Hz	20 Hz	50 Hz	100 Hz	2,000 Hz
Wavelength	340 m	34 m	17 m	6.8 m	3.4 m	17 cm

LUBW

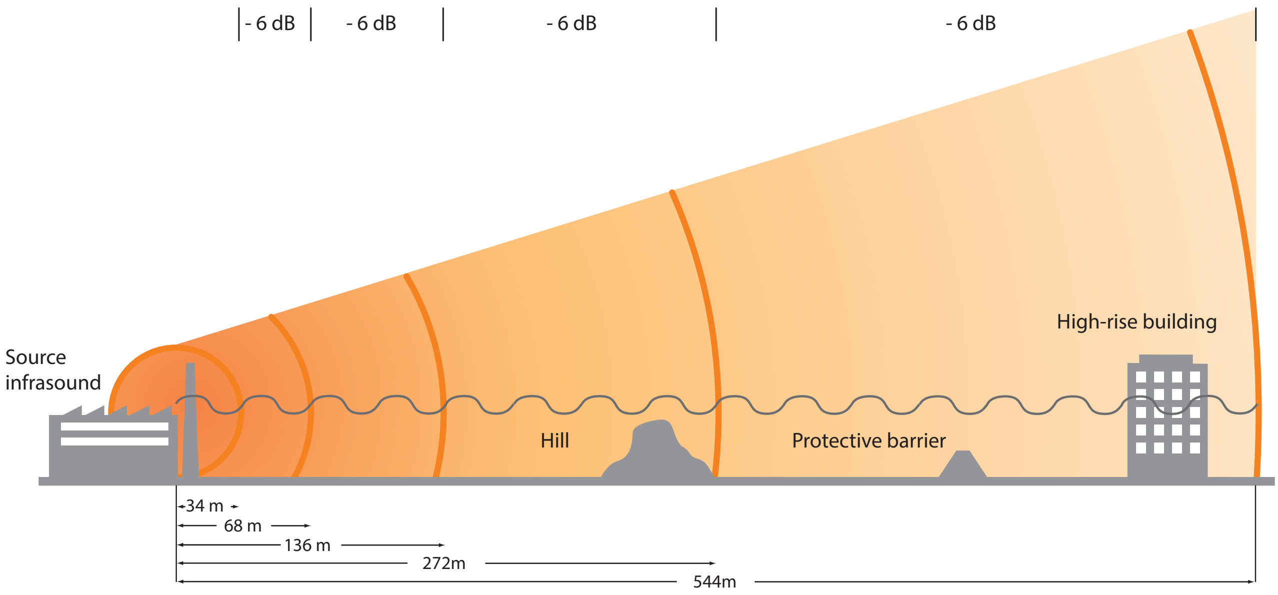


Figure A1-1*: Exemplary presentation of spread of infrasound with a frequency of 10 Hz. The associated wavelength of 34 m is larger than the height of houses, trees and protective barriers. Therefore these hardly absorb the sound. However, the sound pressure level nevertheless decreases according to the same law as for audible sound: Each doubling of distance from the source results in a decrease in sound level of 6 dB. Image source: Bayerisches Landesamt für Umwelt [15]*

A1.3 INCIDENCE AND OCCURRENCE

Infrasound and low-frequency noise are everyday components of our environment. They are produced by a large number of different sources. These include natural sources, such as wind, waterfalls or sea surf, just as much as technical sources, such as heating and air conditioning systems, road and rail traffic, airplanes or speaker systems in nightclubs, etc.

A1.4 EVALUATION

The measurement and assessment of low-frequency noise are regulated in the technical instructions for the protection against noise (TA Lärm [10], please refer to Chapter 7.3 and Appendix A1. 5) as well as the standard DIN 45680 [4]. The impact of noise can be safely determined on the basis of these regulations. In this case the frequency range from 8 Hz to 100 Hz is considered. The crucial aspect when it comes to possible noise pollution is the human hearing threshold or perception threshold, which is outlined in the standard. See also the next section.

An own frequency weighting, the so-called G-weighting, exists for the area of infrasound. The relevantly weighted levels are specified as dB(G) – "decibel G". The A-weighting of noise dB(A) – "decibel A" – is more common, which is derived from human hearing. The G-weighting is focused at 20 Hz. Levels are amplified between 10 Hz and 25 Hz. Above and below that, the valuation curve quickly falls. The purpose of G-weighting is to characterise a situation regarding low frequencies or infrasound with only a single number. A disadvantage is that frequencies below 8 Hz and above 40 Hz hardly contribute at all. For more information please refer to "Frequency Evaluation" in Appendix A3, where you will also find an evaluation curve (***Figure A3-1***).

A1.5 PERCEPTION

In the area of low-frequency noise below 100 Hz there is a smooth transition from hearing, i.e. the sensations of volume and pitch, to feeling. Here the quality and nature of the perception changes. The pitch sensation decreases and does not apply at all for infrasound In general, the following applies: The lower the frequency, the higher the

***Table A1-2**: Hearing and perception threshold (in decibels) in the range of infrasound. The lower the frequency, the louder the noise or sound intensity has to be in order for a person to perceive something. At 8 Hz the sound pressure level has to be at 100 decibels. Humans can hear best in the area of 2,000 to 5,000 Hz. That is where the average hearing threshold is at 0 decibels and even below it (up to minus 5 decibels).*

Frequency (as a third octave centre frequency)	8 Hz	10 Hz	12.5 Hz	16 Hz	20 Hz
Hearing threshold according to DIN 45680 (1997) [4]	103 dB	95 dB	87 dB	79 dB	71 dB
Perception threshold according to draft DIN 45680 (2013) [5]	100 dB	92 dB	84 dB	76 dB	69 dB

LUBW

sound intensity has to be so that the noise is heard at all (see ***Table A1-2***). Low-frequency impact with high intensity is often perceived as ear pressure and vibrations. Permanent exposure to such high noise levels can lead to buzzing, vibrating sensations or a feeling of pressure in the head. In addition to the sense of hearing, other sensory organs can also register low-frequency sound. For example, the sensory cells of the skin convey pressure and vibration stimuli. Infrasound can also affect cavities in the body, such as lungs, sinuses and middle ear. Infrasound of very high intensity has a masking effect for the middle and lower acoustic range. That means: In the case of very strong infrasound, your hearing is unable to perceive quiet tones in frequencies above it.

But where are the limits between hearing, feeling and "no longer perceiving"? ***Table A1-2*** shows some levels of the hearing and perception thresholds for different frequencies. The hearing threshold of DIN 45680 (1997) [4] is defined in such a way that 50 % of the population will no longer perceive the respective frequency below the specified level. The perception threshold of DIN 45680 (2013) [5] is defined so that 90 % of people will no longer perceive the sound below this level. The limit from which low-frequency sound can be heard, varies from person to person. This is nothing unusual, as it is similar to what we are accustomed to regarding audible sound in everyday life. For almost 70 % of people, the hearing threshold lies in a range of ± 6 dB around the values shown in ***Table A1-2***. For particularly sensitive individuals, who make up around two to three percent of the total population, the hearing threshold is at least 12 dB lower. ***Figure A1-2*** provides a graphic depiction of the relationship of the two thresholds. The differences are relatively small.

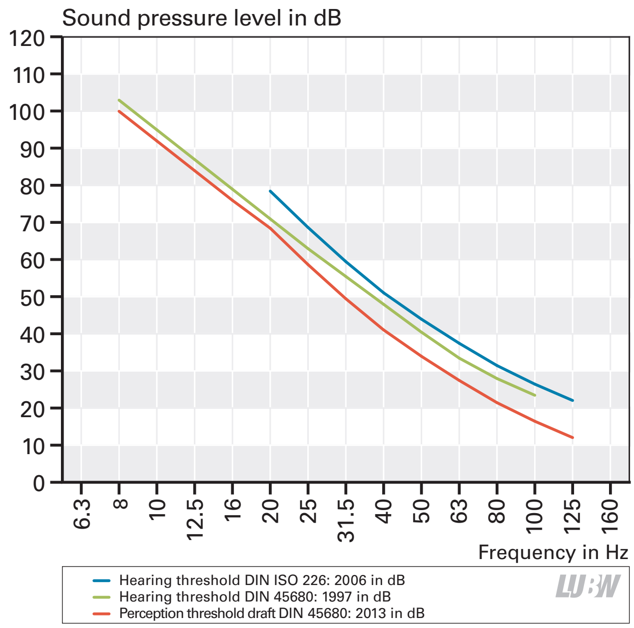


***Figure A1-2**: Representation of hearing and perception threshold according to ISO 226 [29], DIN 45680 (1997) [4] and draft DIN 45680 (2013) [5]. The perception threshold according to the draft of DIN 45680 is roughly 10 dB lower than the values of ISO 226.*

Laboratory tests on the impact of infrasound have shown that high intensities above the perception threshold are tiring and have an adverse effect on concentration, and can influence performance. The best proven reaction by the body is increasing fatigue after several hours of exposure. The balance system can also be affected. Some test persons had feelings of insecurity and anxiety, while others displayed a reduced respiratory rate. Furthermore, as is the case with audible sound, very high sound intensities can lead to a temporary hearing impediment – an effect often known by people who go to nightclubs. Long-term exposure to strong infrasound can also lead to permanent hearing loss. However, the infrasound levels that occur in the vicinity of wind power plants will hardly be able to cause any such effects, as they fall far short of the hearing or perception threshold. In scientific literature, any health effects could so far be shown only at sound levels above the hearing threshold. Below the hearing threshold, no effects on humans caused by infrasound could so far be proven [25].

Appendix A2 – Sources and literature

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Appendix A3 – Explanation of terms and parameters

A-weighting

Frequency-dependent alteration of a noise or sound signal by means of A filter according to DIN EN 61672-1:2003 [22]. See also frequency weighting and dB(A).

Averaging level

See sound pressure level

Background noise

Noise with the wind power plant switched off. It consists particularly of the sound caused by wind in the vicinity and of noise coming from other sources of noise in the vicinity. The background noise may also include sound induced by the wind at the microphone. Also referred to in the report as the operating condition "turbine off".

C-weighting

Frequency-dependent alteration of a noise or sound signal by means of C filter according to DIN EN 61672-1:2003 [22]. See also frequency weighting and dB(C).

dB

Decibel, unit of measurement for the identification of levels, in this case sound pressure level (quod vide).

dB(A)

Decibel A, unit of sound pressure level in A-weighting. See also sound pressure level and A-weighting.

dB(C)

Decibel C, unit of sound pressure level in C-weighting. See also sound pressure level and C-weighting.

dB(G)

Decibel G, unit of sound pressure level in G-weighting. Is used particular with low-frequency noise incl. infrasound. See also sound pressure level and G-weighting.

dB(Z)

Decibel Z, unit of sound pressure level in Z-weighting that corresponds to the linear sound pressure level unweighted in terms of frequency. Formerly also referred to as dB(lin).

Emission

See sound emission

Extraneous noise

Noise that is not caused by the turbine being measured and can temporarily lead to an increase of background noise. Disturbing extraneous noise is excluded from the evaluation by placing markers, and is therefore included neither in the represented total noise nor in the background noise.

Frequency

Number of oscillations per second; the unit is hertz (Hz). The total audible frequency range is divided into:

- Infrasound: Sound with frequencies below 20 Hz
- Audible sound: Sound in the range of 20 Hz to about 16,000 Hz (limit is age-dependent)
- Ultrasound: Sound above roughly 16,000 Hz
- Low-frequency sound: Sound at frequencies below 100 Hz, including infrasound

Frequency weighting (noise)

The frequency content of noise is weighted differently according to the specific objective. In addition to the generally usual A-weighted and C-weighted noise levels, G-weighted and Z-weighted noise levels are also determined and represented in this study.

By default, the frequency weighting A is used for the valuation of sound signals in the normal audible sound range. It approximately constitutes the hearing sensitivity of the human ear in the low and medium sound intensity level. The description and assessment of noise emission and immissions generally follows by means of A-weighted levels. The evaluation of low-frequency noise including infrasound requires separate restrictions of the frequency ranges; A-weighted sound levels that are determined across the entire frequency band are unsuitable for this.

The frequency weighting C approximately corresponds to the auditory sensation of the ear at high volumes. It is applied in particular when assessing noise level peaks in the scope of occupational safety and health. In addition, the

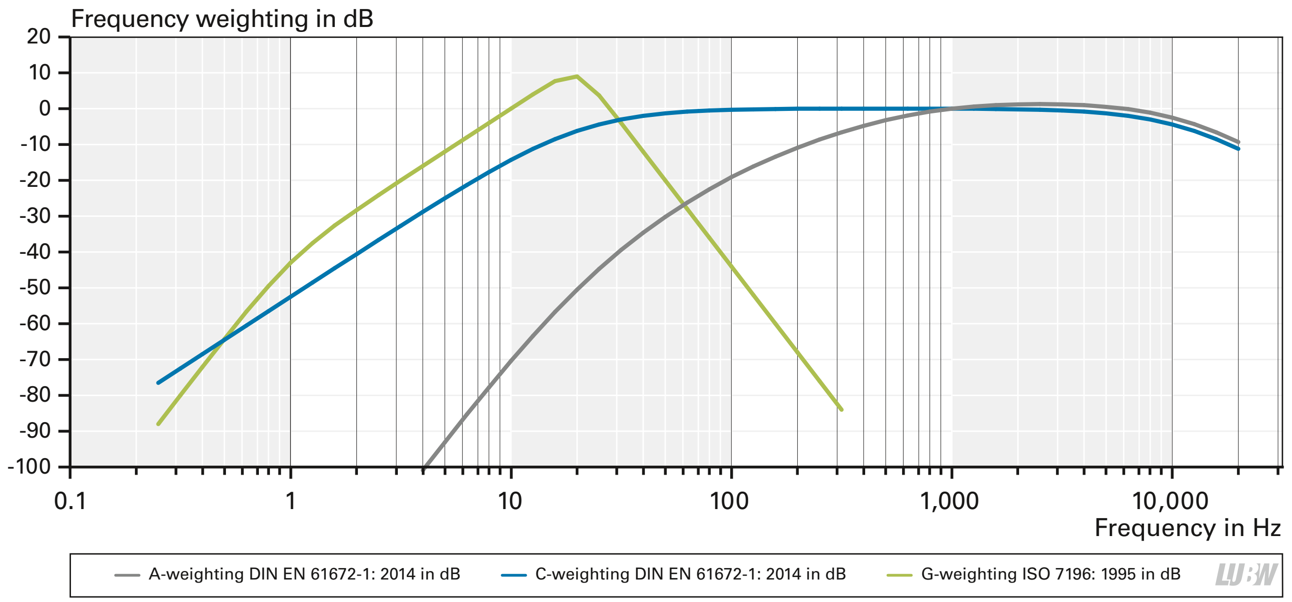

***Figure A3-1**: Course of the frequency weighting curves A, C and G in the range below 500 Hz according to ISO 7196 and DIN EN 61672-1 (2013) [22]*

level difference of measured C-weighted and A-weighted levels is seen as an indicator for possible low-frequency noise contamination in the area of immission control.

The frequency weighting G is a filter that was defined for the effect adaptation of infrasound. Its focus lies at 20 Hz (see Figure A3-1). However, no relevant reference or comparative values are known for the quantitative classification of any infrasound effects or determined G-weighted levels.

The frequency weighting Z (zero) describes a linear band pass filter without any effect on the frequency.

Frequency spectrum

See spectral analysis

G-weighting

Frequency-dependent change of noise or sound signal using G filter according to ISO 7196:1995 [30]. See frequency weighting and dB(G).

Hearing threshold

See Appendix A1.5

Immission

See sound immission

Infrasound

See Appendix A1.1

Level

Logarithm of the relationship of two identical sizes. For the sound pressure level, the ratio of sound pressure, which is caused by noise, to a fixed reference size (hearing threshold) is formed. See also sound pressure level.

L_{eq}

Energy equivalent average of the (time-varying) sound pressure level course within a reference period. See also sound pressure level.

L_{max}

Maximum sound pressure level in a measurement interval. See also sound pressure level.

Low-frequency sound

See Appendix A1.1

Narrowband spectrum

See spectral analysis

Noise

Noise can be considered unwanted, disturbing or harassing sound. While sound can be well-measured and characterized as a physical phenomenon, human feelings also play a part when it comes to noise.

Operating noise

Noise with wind turbine switched on, including background noise. Is referred to as total noise throughout the report.

Perception threshold

The perception threshold used in this report is composed of the perception threshold according to Table 2 in DIN 45680 (2013 draft) [5] and values from literature.

The values of the draft standard are based on DIN ISO 226 [29]; they are 10 dB below the hearing threshold specified therein. For frequencies of 8 Hz to 20 Hz they are supplemented by the values determined by WATANABE & MØLLER [34]. The course corresponds to the 90 % percentile of audible threshold distribution.

Since no standardized threshold levels exist in the frequency range below 8 Hz, the values of the hearing threshold proposed by MØLLER & PEDERSEN [11, Figure 10] were taken for the representations in this measurement report in the range of 1.6 Hz to 8 Hz (***Table A3-1***).

Sound

Put simply, sound consists of compressional waves. Airborne sound is the propagation of pressure fluctuations in the air as a wave motion. If this happens in solid materials, e.g. the floor or walls, it is called structure-borne sound. In order to characterize sound, variables such as sound level (characterizes the strength of the sound) or frequency (denotes the pitch) are used.

Sound emission

The noise coming from a turbine in accordance with § 3 para. 3 BImSchG [2]

Sound immission

The noise effecting humans, animals, etc. in accordance with § 3 para. 2 BImSchG [2]

Sound pressure level L

Often simply referred to as sound level. 20-fold decimal logarithm of the ratio of a given effective value of sound pressure to a reference sound pressure (e.g. hearing threshold), where the effective value of the sound pressure is determined with a standard frequency and time weighting (L in dB). Sound pressure levels of the normal range of hearing are determined primarily by the frequency weighting A and the time rating F according to DIN EN 61672-1 [22] (see also frequency weighting). The types of frequency and time weightings are usually indicated as indices of the formula sign, e.g. L_{AF} in dB(A). The definition of the sound pressure level L for a sound pressure p is:

$$L = 10 \cdot lg \frac{p^2}{p_0^2} (dB) = 20 \cdot lg \frac{p}{p_0} (dB)$$

Here p_0 is a reference sound pressure in the region of the hearing threshold, defined as $2 \cdot 10^{-5}$ Pa. Sound level differences of 1 dB are only just recognisable, differences of 3 dB can be heard clearly. Sound level differences of 10 dB correspond to roughly double or half the impression of loudness respectively.

- The addition of two identical sound levels (doubling of the sound power) leads to an increase of the sum level by 3 dB.
- The reduction of a road's traffic volume by half results in a 3 dB lower level.
- In the case of a single point source, a doubling of distance leads to a reduction of the sound level by 6 dB.

The instantaneous sound pressure level is the current level value of a time-varying noise, for example specified as $L_{AF}(t)$ in dB(A).

The maximum sound pressure level or maximum level is the maximum value of the fluctuating sound pressure level curve within a reference period, referred to as L_{max} in dB. For the frequency weighting A and the time rating F, the level is referred to as L_{AFmax} and specified in dB(A).

The average sound level or equivalent continuous sound level L_{eq} is the energy equivalent mean value of the temporally variable sound pressure level curve L(t) within a reference period, expressed in dB. It is formed according to DIN 45641 [31] or directly with a measuring instrument according to DIN EN 61672-1 [22]. For the frequency weighting A and time weighting F, the time-average sound pressure level is referred to as L_{AFeq} and expressed in dB(A).

Spectral analysis

Spectral analysis is an important tool for the analysis of acoustic signals. The signal is fragmented into defined frequency bands and a sound level is determined for each individual band. A distinction is made between frequency bands of absolute and relative bandwidth.

In the case of narrowband spectra, the frequency range that is to be analysed is divided up into bands of the same absolute width. Here in this report, a bandwidth of 0.1 Hz was consistently used. That enabled a high resolution depiction of the frequency spectra of the sound signal.

Octave and third octave spectra (1/3-octave spectra) are composed of frequency bands of relative bandwidth. The centre frequency of an octave band has a ratio of 1:2 to the centre frequency of the adjacent bands; third octave bands have a ratio of 1:1.26. The starting value for the determination of the centre frequencies is the frequency of 1,000 Hz. The frequency bandwidths within octave or third octave spectra thus differ. The third octave centre frequencies from 1 Hz are: 1 Hz, 1.25 Hz, 1.6 Hz, 2 Hz, 2.5 Hz, 3.15 Hz, 4 Hz, 5 Hz, 6.3 Hz, 8 Hz, 10 Hz, 12.5 Hz, 16 Hz, 20 Hz, 25 Hz, 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz etc. – see also [23].

Third octave representation

Representation of a sound signal in a frequency spectrum. See also spectral analysis and third octave spectrum.

Third octave level

Sound pressure level within a third octave frequency band. See also spectral analysis.

Third octave spectrum

Frequency spectrum in which the frequency range and the corresponding level proportions are divided into thirds. See also spectral analysis.

Total noise

Noise with wind turbine switched on, including background noise. Also referred to in the report as the operating condition "turbine on".

Turbulence intensity

The turbulence intensity (also known as degree of turbulence) was here formed from the average of the quotients of standard deviation and arithmetic mean of the wind speed. It is a measure of the variation of the wind speed (gusts). The turbulence intensity is given in percent and is subject to many influences, e.g. ground roughness, medium wind speed, atmospheric situation or buildings. Its lowest values (5 % or less) are reached over the sea, the highest (20 % or more) are reached over built-up areas and forest [32]. While the turbulence intensity has no significant effect on measurements in the A level range (audible sound) [33], this is not documented for low frequencies. Here an influence can by all means be expected. Some manufacturers of wind turbines link the warranty condition for their guaranteed values of acoustic power to maximum turbulence intensities during measurement, e.g. 16 %. The turbulence intensity is determined in accordance with DIN EN 61400-11 [6].

Vibrations

Vibrations are oscillations of solid bodies.

Vibrational immissions

Vibrational immissions are the oscillations that occur at the measurement point.

Vibration velocity

The vibration velocity (speed) is the velocity of an oscillating mass at the measurement point in the predetermined measurement direction, stated in millimetres per second (mm/s). This variable is based on the assessment of vibration impacts on buildings and on people in buildings. The vibration is defined initially through the ground motion, i.e. the vibration displacement (amplitude), characterized as a function of time. The vibration velocity can then be derived by differentiating with respect to time.

***Table A3-1**: The hearing threshold levels used to represent the perception threshold in the report according to [5] and [11]*

Source	Third octave centre frequency in Hz	Perception threshold level W_{Terz} in dB
Threshold level - taken from [11]	1.60	124.0
	2.00	122.0
	2.50	120.0
	3.15	117.0
	4.00	113.0
	5.00	108.5
	6.30	105.0
Threshold level - taken from [5]	8.0	100.0
	10.0	92.0
	12.5	84.0
	16.0	76.0
	20.0	68.5
	25.0	58.7
	31.5	49.5
	40.0	41.1
	50.0	34.0
	63.0	27.5
	80.0	21.5
	100.0	16.5
	125.0	12.1

LUBW

Vibration severity

In the vibration frequency range of 1 Hz to 80 Hz that is relevant for the perception of vibration, the perceptibility is proportional to the vibration velocity. Below approximately 10 Hz, the perception at lower frequencies is significantly lower. This is taken into account for the evaluation of measurement data through the use of special filtering, the so-called KB-evaluation according to DIN 4150 Part 2. Inputs above 80 Hz are cut off by a blocking filter (band limitation) as they do not contribute to perception. The band-limited, frequency and time-weighted signal is designated as weighted vibration severity $KB_F(t)$. The highest value achieved during the assessment time, the maximum weighted vibration strength KB_{Fmax}, is an important evaluation parameter for the tactility of vibration effects.

Wavelength

For a wave (here acoustic wave), the distance from a "wave crest" to the next "wave crest" or "trough" to "trough" is referred to as wavelength (general distance from one point to the next point of the same phase). The wavelength is related to the frequency as follows: The wavelength is the propagation speed divided by the frequency of the wave. Sound waves in air can generally be registered by the human ear in the approximate wavelength range of 2 cm to about 20 m.

Z-weighting

Unweighted or linear noise or sound signal according to DIN EN 61672-1:2003 [22]. See frequency weighting and dB(Z).

Appendix A4 – Measuring systems used

Below is a description of the used measurement systems and equipment. The sound level measuring instruments used meet the specifications for Class 1 for sound level meters according to IEC 61672. The dynamic range of the microphone capsule type 40AZ is 14 dB(A) to 148 dB according to the manufacturer, the usable frequency range is 0.5 Hz to 20 kHz. For the remaining microphone capsules used, the usable frequency range is 3.15 Hz to 20 kHz.

Measurements at wind turbines (Section 4)

- 4 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ on reverbrant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  - Air pressure, humidity and temperature sensor type DTF 485, manufacturer: Reinhardt System- und Messelectronic GmbH, D-86911 Diessen-Obermühlhausen
  - Wind sensor type WMT 701, manufacturer: Vaisala GmbH, D-22607 Hamburg

- 1 acoustic emission measurement system type RoBin, manufacturer: Wölfel Meßsysteme, D-97204 Höchberg

- 4 vibration meters type SM 6 (triaxial) according to DIN 45669, consisting of:
  - Sensor Nederland / Wölfel Meßsysteme
  - Supply and AD conversion: System Red Sens with radio modules
  - Coupling of the measuring sensors according to DIN 45669-2. The measuring chain was checked before and after the measurement.

- 1 data acquisition system, consisting of:
  - Notebook Dell Latitude with Elovis radio antenna for Red Sens
  - Measurement and evaluation software MEDA
  - Sampling: upper limit frequency, 400 Hz corresponds to sampling rate of 976.6 μs, manufacturer: Wölfel Meßsysteme, D-97204 Höchberg

Road traffic measurements (Section 5.1)

- 1 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" Type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 2 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40AZ, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  - Air pressure, humidity, temperature and wind sensor type WXT 520, manufacturer: Vaisala GmbH, D-22607 Hamburg

LUBW Long-term measuring stations (Section 5.2)

- 2 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  - Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  - Free-field microphone 1/2" type 40CD, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 2 meteorology sensors, consisting of:
  - Precipitation monitor model 5.4103.10.00, manufacturer: Adolf Thies GmbH & Co. KG, D-37083 Göttingen
  - Temperature and humidity sensor type HMP 155, manufacturer: Vaisala GmbH, D-22607 Hamburg

– Ultrasonic aemometer type 85004, manufacturer: R. M. Young Company, USA-2801 Aero Park Drive

Measurements at motorway (Section 5.3)

- 3 sound level meters combinations type NOR 140, consisting of:
  – Sound level analyser type Nor 140, manufacturer: Norsonic AS, N-3421 Lierskogen
  – Free-field microphone 1/2" type 1225, manufacturer: Norsonic AS, N-3421 Lierskogen

Interior noise measurements car, minibus (Section 5.4)

- 1 sound level meter combination type NOR 140, consisting of:
  – Sound level analyser type Nor140, manufacturer: Norsonic AS, N-3421 Lierskogen
  – Free-field microphone 1/2" type 1225, manufacturer: Norsonic AS, N-3421 Lierskogen

Urban background measurements (Section 6)

- 2 sound level meter combinations type DUO Smart Noise Monitor, consisting of:
  – Sound level analyser type DUO, manufacturer: 01dB-Metravib SAS, F-69760 Limonest
  – Free-field microphone 1/2" type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 sound level meter combination DUO Smart Noise Monitor, consisting of:
  – Sound level analyser type DUO, manufacturer: 01dB-Metravib SAS, F-69760 Limonest
  – Free-field microphone 1/2" type 40AZ, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  – Air pressure, humidity, temperature and wind sensor type WXT 520, manufacturer: Vaisala GmbH, D-22607 Hamburg

Measurements in a residential building (Section 7)

- 1 sound level meter combination type NOR 140, consisting of:
  – Sound level analyser type Nor 140, manufacturer: Norsonic AS, N-3421 Lierskogen
  – Free-field microphone 1/2" type 40AZ, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 sound level meter combination type NOR 140, consisting of:
  – Sound level analyser type Nor 140, manufacturer: Norsonic AS, N-3421 Lierskogen
  – Free-field microphone 1/2" type 1225, manufacturer: Norsonic AS, N-3421 Lierskogen

Measurements in rural area (Section 8.1)

- 2 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  – Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  – Free-field microphone 1/2" Type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 sound level meter combinations DUO Smart Noise Monitor, consisting of:
  – Sound level analyser type DUO, manufacturer: 01dB Metravib SAS, F-69760 Limonest
  – Free-field microphone 1/2" type 40AZ on reverberant plate with primary and secondary wind screen in accordance with IEC 61400-11, manufacturer: G.R.A.S. Sound & Vibration A/S, DK-2840 Holte

- 1 meteorology sensor, consisting of:
  – Air pressure, humidity, temperature and wind sensor type WXT 520, manufacturer: Vaisala GmbH, D-22607 Hamburg

Note on the inherent noise of the measuring chain

In order to determine the minimum noise limit of the deployed acoustic measuring chain, sound level measurements were carried out inside buildings at two different locations during the night. The locations were chosen so that the least possible background noise was at hand. The measured values in the range of 1 Hz to 1 kHz are at least 20 dB below the sound levels to be determined here. The influence of the inherent noise of the measuring chain on the measurement results is therefore negligible.

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Evaluation of Wind Turbine Noise in Japan

Akira SHIMADA[1], Mimi NAMEKI[2]

[1] Ministry of the Environment, Office of Odor, Noise and Vibration, Tokyo, Japan (corresponding author)
[2] Ministry of the Environment, Office of Odor, Noise and Vibration, Tokyo, Japan

Corresponding author's e-mail address: oto@env.go.jp

ABSTRACT

In order to tackle with wind turbine noise (WTN) related complaints, Ministry of the Environment of Japan (MOEJ) set up an expert committee in 2013. In November 2016, the committee published a report on investigation, prediction and evaluation methods of WTN. The report compiles recent scientific findings on WTN, including the results of nationwide field measurements in Japan and the results of review of the scientific literature related to health effects of WTN. The report sets out methodology for investigation, prediction and evaluation as well as case examples of countermeasures. A noise guideline for wind turbine, which suggests WTN should not be more than 5dB above the residual noise where residual noise levels are above 35-40dB, is also presented in the report. MOEJ is developing a WTN noise guideline and a technical manual for WTN investigation based on the report. Both documents will be finalized in the fast half of 2017.

INTRODUCTION

Among renewable energy sources, wind power generation is an important energy sources that emits neither air-polluting substances nor greenhouse gases and can also contribute to energy security because the power can be generated by a natural resource readily available in Japan. The Basic Energy Plan of Japan (Cabinet decision in April, 2014) regards wind power generation as an energy source that can be made economically viable because its generation cost could be as low as that for thermal power generation if it could be developed on a large scale.

The number of wind power facilities installed in Japan started to increase around 2001, and 2,034 units were installed by 2014 (as of the end of March, 2015) [1]. According to the Supplementary Materials for the Long-term Energy Supply and Demand Outlook issued by the Agency for Natural Resources and Energy in July, 2015, approximately 10 million kW of wind power is expected to be installed by 2030, which represents a nearly four-fold increase from the existing installed wind power capacity of approximately 2.7 million kW [2].

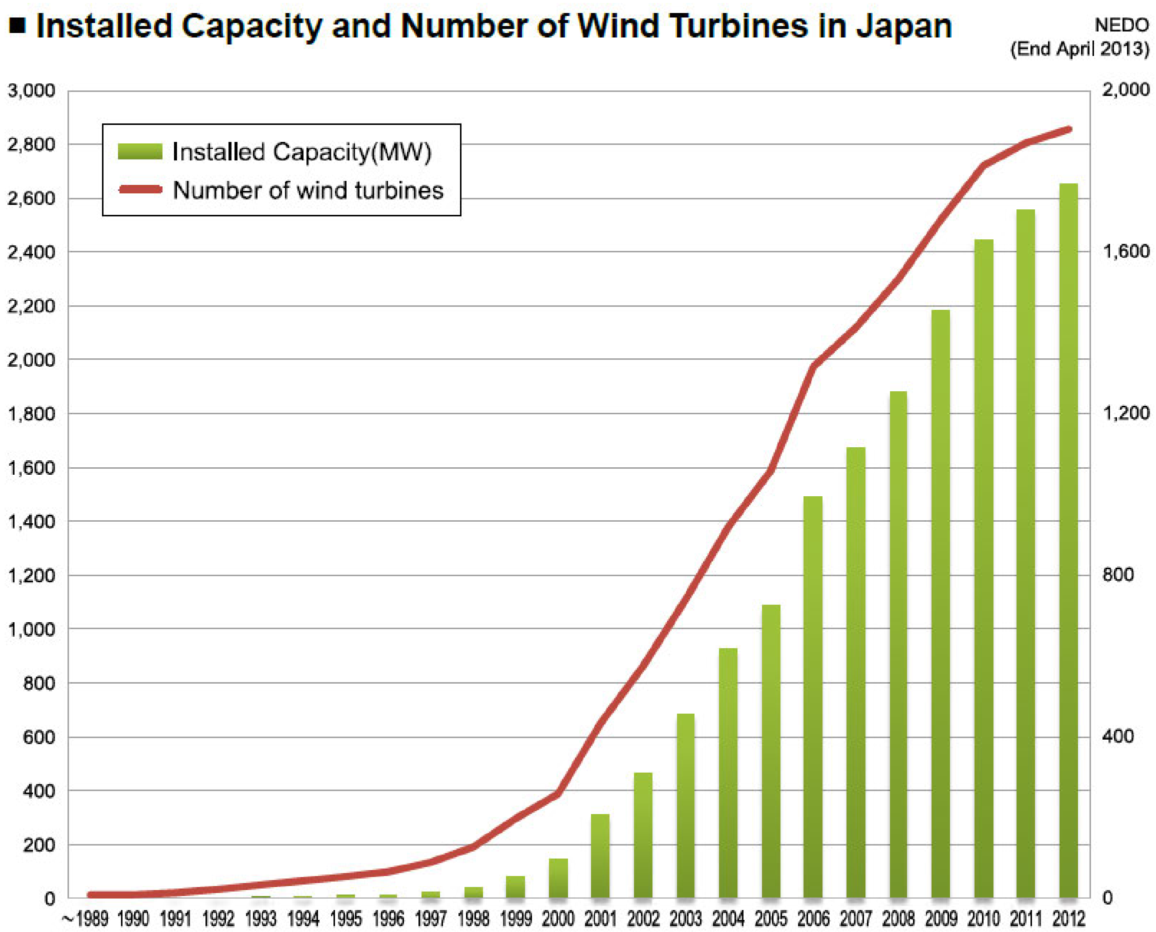

Figure 1: Installed capacity and number of wind turbines in Japan (Source: NEDO)

Wind power facilities emit a certain amount of noise due to their power generation mechanism in which blades rotate by catching wind to generate power. While the noise level is normally not significantly large, there are cases where even a relatively low level of noise causes complaints as wind power facilities are often constructed in agricultural/mountainous areas that have suitable weather conditions including wind direction and velocity that were originally quiet. There have not only been noise complaints but also complaints of inaudible sound of a frequency of 20 Hz or less.

Against such a backdrop, as a result of the amendment of the Order for Enforcement of the Environmental Impact Assessment Act in October, 2012, the establishment of wind power stations came to be classified as relevant projects under the Act and discussions on the environmental impact assessment of wind power facilities have taken place.

In assessing the impact of noise resulting from the installation of a facility, the procedure of environmental impact assessment performed before installation examines "the extent to which such noise can be feasibly avoided or reduced" and, if applicable, "whether it is intended to be consistent with standards or criteria given by the Japanese government or local municipalities from the perspective of environmental protection." For the former examination, the extent to which the impact of noise resulting from the implementation of the relevant project can be feasibly avoided or reduced is assessed by comparing multiple countermeasures in terms of the structure, layout, output, the number of units, and technical noise reduction measures in accordance with the maturity of the project plan. The assessment can also be performed by examining to what extent more feasible technology can be incorporated, etc. Specifically, assessment is made from such viewpoints as whether the local noise level will not be significantly raised, whether the layout plan for the project secures a sufficient distance between the facility and residences, etc.

The Environmental Quality Standards for Noise are generally used for the Environmental Impact Assessment. However, the standards are set based on traditional environmental noise (i.e. traffic noise or noise from factories), not in terms of noise generated from wind power facilities (hereinafter, "wind turbine noise") which has unique acoustical characteristics such as amplitude modulation sound. It is thus necessary to develop methods relevant to the investigation, prediction, and evaluation of wind turbine noise based on the latest scientific findings.

The Ministry of the Environment of Japan (hereinafter, "MOEJ") has set up an expert committee and examined ideas and issues about methods for investigating, predicting, and assessing wind turbine noise from 2013 to 2016. The expert committee published a report on the investigation, prediction and evaluation methods of wind turbine noise in November 2016. During the development of the report, the MOEJ started a one-month public comment period. All comments were considered, and changes were made to the report where appropriate. The report compiles recent scientific findings on wind turbines in terms of noise, including the results of nationwide field measurements in Japan and the results of review of the scientific literature related to the health effects of wind turbine noise. The report sets out methodology for investigation, prediction and evaluation as well as case examples of countermeasures. Based on the report, MOEJ plans to develop a wind turbine noise guideline and a technical manual for wind turbine noise investigation in the fast half of 2017.

This report introduces the report by the expert committee, the wind turbine noise guideline and the technical manual for wind turbine noise investigation.

OUTLINE OF THE REPORT

The report by the expert committee consists of three parts. The first part explains key findings from past researches, namely the field survey measuring wind turbine noise in Japan and a literature review on wind turbine noise and human health. The second part proposes methods for investigating, predicting and evaluating wind turbine noise. A guideline on wind turbine noise is proposed in this part. The third part states the actions recommended by the expert committee. The following chapters summarize those three parts of the report.

KEY FINDINGS

Findings from the field study

Field surveys measuring wind turbine noise conducted in Japan from 2010 to 2012 revealed the following.

In terms of spectral characteristics, wind turbine noise generally has a spectral slope of -4 dB per octave. It has a 1/3 octave band sound pressure level in all parts of the super-low frequency range, which means 20 Hz or lower, is below the ISO threshold of hearing for pure tones and the criterion curve for the evaluation of low frequency noise proposed by Moorhouse et al. (Fig. 2). Super-low frequency range components of wind turbine noise are at imperceptible levels. Therefore, wind turbine noise is not an issue caused by super-low frequency range.

In regard to the audible frequency range, in the range from about 40 Hz and above, the 1/3 octave band sound pressure level is above the said criterion curve and the threshold of hearing defined by ISO 389-7. Therefore, wind turbine noise should be regarded as "audible" sound (noise) in discussing it.All papers must contain an abstract of max. 180 words. A concise and factual abstract is required. The abstract should state briefly the purpose of the research or project, the principal results and major conclusions. An abstract is often presented separately from the paper, so it must be able to stand alone. For this reason, references should be avoided, but if essential, then cite the author(s) and year(s). Your abstract will be published in the printed and in the online program of the congress.

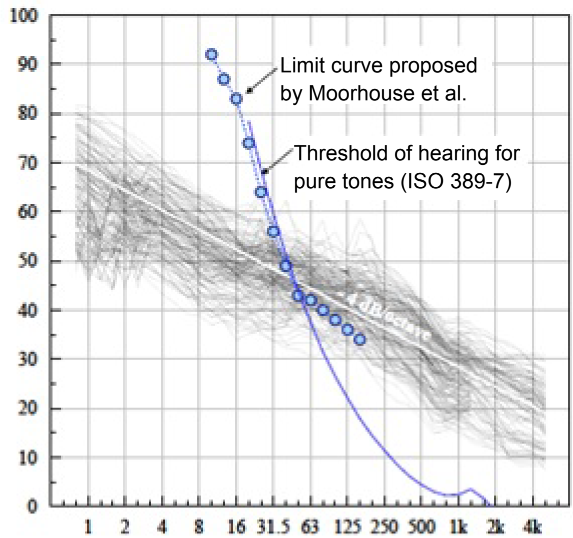

Figure 2: Results of the analysis of frequency characteristics of wind turbine noise (at 164 locations in the vicinity of 29 wind power facilities in Japan)

Noise exposure levels of nearby residents from wind power facilities are distributed in the range of 26–50 dB in time-averaged A-weighted sound pressure levels. While this implies that wind turbine noise is not significantly higher than other types of environmental noise, it can cause serious annoyance to those living residential areas in the vicinity of wind power facilities located in extremely quiet agricultural/mountainous areas.

Low-frequency components of wind turbine noise obtained from field measurements were within the range of those of other environmental sounds.

In Japan, it is known that the following relation holds between LAeq, which properly excludes non-relevant noise, and LA90: LAeq≒LA90+2 dB

It is also generally said that acoustic isolation is not always effective for noise from wind power facilities because it contains more low-frequency components. In a quiet environment with little noise of other types, it is relatively more easily heard than ordinary noise is.

Findings from the literature review on health effects

After careful assessment of the evidence obtained from peer reviewed research results from around the world, it has been concluded that wind turbine noise has likely no negative effects on human health.

However, amplitude modulation and the tonal sounds of wind turbine noise tend to increase annoyance. Existing research results indicate that wind turbine noise over 35 – 40 dB raises annoyance and that the risk of sleep disturbance may increase accordingly.

No clear association is seen between infrasound or the low-frequency noise of wind turbine noise and human health.

Some research results have suggested that wind turbine noise related annoyance is also affected by other issues such as visual aspects or economic benefits.

METHODS FOR INVESTIGATING AND PREDICTING WIND TURBINE NOISE, A PERSPECTIVE FOR ITS EVALUATION, AND RESPONSES AGAINST IT

In light of the findings described in Section 2, the issue of wind turbine noise should be taken not as one of super-low frequency sound below 20 Hz but as one of "audible" sound (noise), and it should be basically measured at the A-weighted sound pressure level. We here summarize matters to be noted in conducting an investigation and/or the prediction of noise before and after installing wind power facilities and a perspective for wind turbine noise evaluation.

Investigation and prediction before installation

Matters to be noted upon an investigation

In selecting a method for investigation, it is necessary to collect various kinds of information in light of business and regional characteristics in order to conduct prediction and evaluation appropriately. Particularly with regard to wind turbine noise, it is important to distinguish and discuss three major issues:

(1) Sound source characteristics

It is necessary to pay attention to:

- information on the wind power facility concerned, including its specifications, manufacturer, model number, hub height, rotor diameter, rated wind velocity, and power generation;
- the sound power level of the generated noise;
- the A-weighted overall value and frequency characteristics (including the 1/3 octave band sound power level) of the sound power level at the rated (maximum) output (to grasp the situation of maximal environmental impact);
- A-weighted overall values and frequency characteristics (including the 1/3 octave band sound power level) of sound power levels under different wind velocities;
- pure tonal frequency components (to be determined in accordance with IEC 61400-11:2012); and
- existing data pertaining to the same model in operation.

(2) Propagation characteristics

In Japan, wind power facilities are often installed in agricultural/mountainous areas. Sound waves emitted from a wind power facility installed in an agricultural/mountainous area are affected by various factors before propagating to a sound receiving point (assessment point), in comparison with one installed on a large, flat piece of land such as a plain or desert. Its noise level and frequency characteristics tend to change due to phenomena including reflection, absorption, transmission, refraction, and diffraction. It is therefore necessary to pay attention to:

- phenomena such as the reflection, absorption, or diffraction of wind turbine noise due to undulating terrain or ridges,
- the state of the ground surface (including rivers and lakes), and
- meteorological information such as wind conditions including wind direction, velocity, and frequency.

(3) Information on a sound receiving point (assessment location)

With regard to locations where an investigation is conducted, focusing on the daily life and activities of residents in the vicinity of a wind power facility, it is necessary to pay attention to:

- the configuration of establishments particularly requiring consideration for environmental conservation such as schools and hospitals and the outline of housing configuration (including the structure of each house), and
- the state of the acoustic environment (degree of quietness) of the area in question.

(4) The specific method for investigation

In measuring residual noise in a given area, it is necessary to pay attention to the following.

a. Sound to be excluded

Sounds of the types given below should be excluded. Since wind power facilities operate when wind is blowing, noises caused by wind such as the sound of rustling leaves are not excluded. ("Wind noise" generated by wind hitting a sound level meter's microphone is excluded, however.)

i) transitory noise such as the sound of automobiles passing nearby and aircraft noise

ii) artificial sound not occurring regularly such as sound generated by accidents/incidents, vehicles driven by hot-rodders, emergency vehicles, etc.

iii) natural sound not occurring regularly such as sound generated by natural phenomena including rain and defoliation, animals' cries, etc.

iv) sound incidental to measurement such as the voice of a person talking to a measurer, sound of tampering with measuring instruments, etc.

b. Surveying and other equipment

As the wind is generally strong in areas around wind power facilities, it is important to use a windbreak screen in order to avoid the effects of wind noise to the extent possible when measuring residual noise. Several kinds of urethane spherical windbreak screens of different diameters are commercially available. In general, the larger the diameter of such a screen is, the less likely a sound level meter inside the screen will be affected by wind noise. Installing a windbreak screen can reduce the impact of wind noise up to a wind velocity of around 5 m/s.

c. Survey areas and locations

Considering the propagation characteristics of wind turbine noise, the survey targets areas susceptible to an environmental impact by wind turbine noise, such as residential areas in the vicinity of a wind power facility (generally within a radius of about 1 km from a wind turbine). An area in which a quiet environment should be conserved such as hospital premises may be included in these target areas. In selecting specific survey locations in the survey areas, in addition to locations where a wind power generation facility is planned to be installed, such locations are to be selected that are immune to local impacts of particular sound sources where the average level of noise in the relevant area can be assessed, including residential areas around the wind power generation facility. Measurement is to be performed at an outdoor location 3.5 m or more distant from a reflective object, excluding the ground.

d. Survey period and hours

In order to grasp conditions throughout the year accurately, a survey is to be conducted in each period of the year for different typical meteorological conditions under which a wind turbine operates (for instance, each season if meteorological conditions vary greatly by seasons).

The period of a single survey should be appropriately determined in consideration of the time variation of noise due to the impact of meteorological conditions and other elements. As measurement values may be unstable depending on wind conditions, a survey should be performed for three or more consecutive days in principle. The survey should be conducted both during the day (6:00–22:00) and at night (22:00–6:00) hours.

Matters to be noted in prediction

As mentioned above, in Japan, wind power facilities are often installed in agricultural/mountainous areas. In comparison with cases where such a facility is installed on a large, flat piece of land such as a plain or desert, sound waves emitted from a wind power facility installed in a mountainous area diffuse in a more complicated manner as they propagate due to the influence of geological states, vegetation, meteorological conditions such as wind conditions, etc. In addition, it should be noted that the propagation of wind turbine noise is extremely complicated as it is subject to attenuation by distance, reflection and absorption by the ground surface, reflection and diffraction by acoustic obstructions, attenuation by atmospheric absorption, etc.

Among the prediction methods used, while "ISO 9613-2：1996" allows incorporation of more detailed conditions, the prediction calculation becomes rather complex. Furthermore, there is the problem of how the reflection rate should be calculated in cases where the effect of reflection by the ground surface becomes an issue, as is the case with a wind turbine installed on a ridge.

The New Energy and Industrial Technology Development Organization (hereinafter, "NEDO") published a prediction method for the environmental impact assessment of wind power generation in July, 2003 (revised as the second version in February, 2006). This models wind power facilities as sound source points and uses sound power levels provided by manufacturers of wind power generators. This method takes into account distance attenuation due to sound diffusion in the propagation process and attenuation by atmospheric absorption. While this method can be used easily, it is difficult to consider meteorological effects, etc.

It is necessary to pay attention to such characteristics of methods in making predictions.

Survey after the installation of a wind turbine

As stated in Section 3.1, predicting wind turbine noise involves elements with large uncertainty such as emission characteristics of noise from the source and effects of meteorological conditions as well as the terrain and structures in the propagation process. Predicted values before the installation of a wind turbine and measured values after installation may sometimes differ greatly.

We here summarize matters to be noted in a survey after the installation of a wind turbine.

(1) Conditions of measurement

It is necessary to grasp the conditions of measurement and other relevant local matters that may impact the propagation of noise. At least, one should grasp the wind direction and velocity at the nacelle height, the variation of power output, and meteorological data required for calculating the attenuation by atmospheric absorption (wind direction and velocity, temperature, and humidity).

(2) Survey method

Wind turbine noise varies greatly according to the wind conditions, and a wind turbine often starts and suspends operation repeatedly. Therefore, measurement should be performed in appropriate hours considering the state of operation of the wind power facility in question. For example, a method is conceivable that measures the average level in a 10-minute period in which wind turbine noise is stable (10-minute equivalent noise level: L_{Aeq}, 10 min) and regards it as the representative value. If the relevant wind power facility operates steadily for many hours, it is effective for obtaining robust data, for instance, to measure noise for 10 minutes every hour on the hour and calculate the average energy over the entire period of time.

For measurement locations, period, etc., refer to what is noted for a survey before the installation.

(3) Survey Results

The representative value of a survey after the installation of a wind power facility should be taken as the A-weighted equivalent sound pressure level measured over a period of time in which the effect of wind turbine noise is at its maximum and in which the effect of background noise is low (e.g. during night time). It is also required to confirm whether there is any pure tonal component.

The equivalent noise level during operation can be estimated by adding around 2 dB to the noise level exceeded for 90% of the measurement period (L_{A90}).

Evaluation of wind turbine noise

With regard to the evaluation of wind turbine noise, the expert committee proposed the development of a new guideline. Detailed proposals on the new guideline are as follows:

- The guideline should be applied when a wind power facility will be newly built or a wind power facility will be retrofitted to add a power generation facility.
- As a guideline value, “residual noise + 5dB” is proposed.
- Residual noise should be measured when wind is steady.
- In low noise environments, a lower limit for wind turbine noise should be set since there is no acoustic benefit. Wind turbine noise should be limited to 35dB in the

areas where background noise is lower than 30 dB and where some noise sensitive locations exist. For other areas, 40 dB should be set as the lower limit of wind turbine noise.

- To apply the guideline, locations where wind turbine noise might affect residents' daily activities (e.g. nearest dwellings) should be selected.
- To conserve the indoor environment, evaluation should be made based on outside noise data (both day and night).

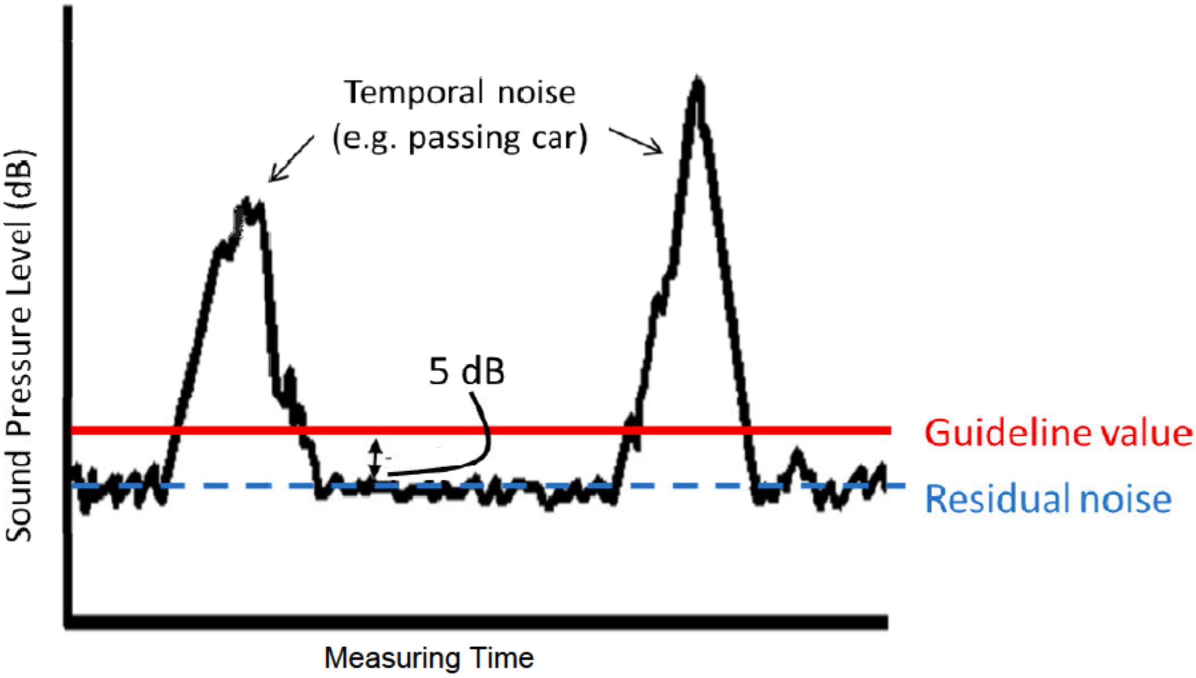

Figure 3: Image of relationship between residual noise and guideline value

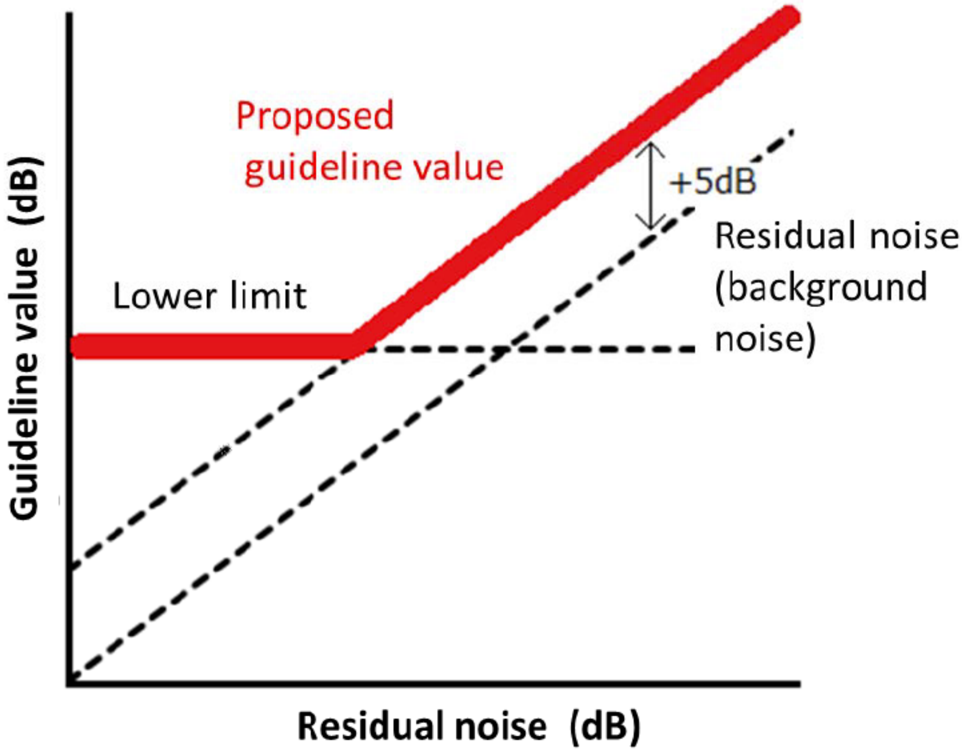

Figure 4: Image of guideline value

RECOMMENDED ACTION

The expert committee recommended actions to be taken by stakeholders.

As for operators and manufacturers of wind power facilities, recommended actions include accumulating survey data after the installation of wind power facilities, promoting R&D for noise abatement technologies such as low noise blades. .

As for administrative agencies (the government of Japan and local municipalities, recommended actions include developing a wind turbine noise guideline and a detailed technical manual for investigation.

As for all parties concerned, recommended actions include facilitating communication among stakeholders.

WIND TUBINE NOISE GUIDELINE AND TECHINICAL MANUAL

On the basis of the report by the expert committee, MOEJ is developing a wind turbine noise guideline and a detailed technical manual for wind turbine noise investigation to be finalized in the fast half of 2017.

The key points of noise guideline are as follows:

- All parties related on wind turbine should consider the social, geographical, or meteorological characteristics of the location of wind power generations and the noise from them.
- The guideline aims to prevent possible noise related effects to protect living environment (indoor environment) of neighborhood residents before installation of a new wind power facility.
- A guideline value of wind turbine noise should be set as “residual noise + 5dB” where residual noise level is above 35-40 dB.
- Evaluation should be made based on outside noise data both day and night.

The technical manual covers following points:

- Methods to investigate wind speed and directions,
- Methods to investigate residual noise including site selection, sampling period, and necessary equipment,
- Methods to investigate wind turbine noise including site selection, sampling period, and necessary equipment
- Methods to process collected data
- Recommended formats to record data

CONCLUSION

This paper summarizes the basic ideas and methods proposed by the report published by the expert committee on wind turbine noise in November 2016, a noise guideline and a technical manual for wind turbine noise investigation which will be finalized in the fast half of 2017.

Acknowledgements

The authors wish to acknowledge the members of expert committee of wind turbine noise.

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WIND TURBINES IN DENMARK

DANISH ENERGY AGENCY

CONTENTS

FOREWORD


Photo: Wind Turbine Secretariat

This booklet, *Wind Turbines in Denmark*, aims to provide a general introduction to wind turbines in Denmark. It is directed at municipalities, wind turbine players and other interested parties, who will gain insight into relevant topics relating to wind turbines. The descriptions of the individual topics are intended to answer and elaborate on questions that are frequently asked about wind turbines.

In 2007 the Danish Government's Planning Committee for Onshore Wind Turbines published a report containing, among other things, a recommendation that there should be an increase in government information and advice on wind power for the municipalities and the public in general. This booklet is a response to that recommendation.

Further information on wind turbines can be found on the websites of the Danish Energy Agency (**www.ens.dk**), the Agency for Spatial and Environmental Planning (**www.blst.dk**), the Danish Environmental Protection Agency (**www.mst.dk**), and CAA-Denmark (**www.slv.dk**). References to other relevant websites can be found elsewhere in the booklet.

Section 1 ("Wind power – one of the solutions to the challenges of energy policy") gives an introduction to the evolution of renewable energy, the goals of energy policy, and the challenges presented by wind power. Section 2 ("The history of Danish wind power") provides facts about wind turbines and their development up to the present day. Section 3 ("Wind turbines and their surroundings") describes the environmental features of wind turbines, highlighting shadow and noise as local challenges of wind turbines.

Section 4 ("Onshore wind turbines") covers the general regulations for erecting onshore turbines and the special regulations that apply for household wind turbines and small wind turbines. Section 5 ("Offshore wind turbines") describes offshore wind turbines and the administrative 'one-stop shop' set-up.

Section 6 ("New schemes in the Danish Promotion of Renewable Energy Act") discusses the four schemes that were agreed politically in the *Energy Policy Agreement of 21 February 2008* and incorporated into the *Danish Promotion of Renewable Energy Act*: namely, the loss-of-value scheme, the option-to-purchase scheme, the green scheme, and the guarantee scheme. Section 7 ("Tariffs for electricity produced by wind turbines") presents the price supplements that are paid for wind turbine electricity. Finally, Section 8 ("Incorporation of wind power into the electricity system") examines wind power production in the context of the overall European electricity system.

Sections 3, 4 and 6 are aimed in particular at the municipalities and the planning that they undertake with regard to the erection of onshore wind turbines.

This booklet has also been published in Danish.

1. WIND POWER – ONE OF THE SOLUTIONS TO THE CHALLENGES OF ENERGY POLICY

Factbox

WIND TURBINES IN THE *ENERGY POLICY AGREEMENT*

As part of the efforts to secure the target of a 20% wind power share in 2011, the *Energy Policy Agreement of 21 February 2008* introduces a number of improvements in the conditions for erecting wind turbines:

- The supplement to the market price for new onshore wind turbines is increased to DKK 0.25 per kWh for 22,000 full-load hours. DKK 0.023 per kWh as compensation for balancing costs, etc., is retained
- The scrapping scheme is amended to give an additional price supplement of DKK 0.08 per kWh for 12,000 full-load hours. The deadlines for connecting new wind turbines to the grid under the scrapping scheme are extended
- The municipalities are required to plan for 75 MW wind turbines in each of the years 2010 and 2011
- A number of schemes are introduced to promote local acceptance of new onshore wind turbines: 1) a loss-of-value scheme gives neighbours the right to claim compensation for loss of value on their property if the loss is assessed to be at least 1% of the property's value; 2) an option-to-purchase scheme gives the local population the right to purchase at least 20% of new projects involving wind turbines with a total height of more than 25 metres; 3) a guarantee fund of DKK 10 million helps local wind turbine owners' associations to finance preliminary investigations, etc.; 4) a green scheme offers subsidies for municipal projects that enhance scenic values in local areas where new wind turbines are erected
- A total of 400 MW offshore wind turbine capacity is being tendered out and is expected to be put into operation in 2012 (the Anholt project)
- The *Offshore Wind Turbine Action Plan of September 2008* is being updated, and earlier site development is being considered. Clearer guidelines are being set out for the establishment of new offshore wind turbine projects via an "open-door" procedure

1.A. THE CHALLENGES OF ENERGY AND CLIMATE POLICY

Since the first oil crisis in 1973 Denmark has transformed its energy supply and developed its own production of oil, natural gas and renewable energy. At the same time, energy has been greatly optimised so that, in spite of considerable economic growth during this period, there has only been a marginal increase in energy consumption. Denmark is therefore better prepared for international energy crises than most other countries, regardless of whether the challenges relate to supply or price. Furthermore, Danish emissions of the greenhouse gases covered by the Kyoto Protocol were reduced by around 8% in the period 1990-2008.

In spite of these results, Danish society is still facing major challenges in its energy and climate policies. Denmark is expected, with its existing fields and finds, to be a net exporter of oil and natural gas for about 10 more years, although technological advances and any new finds may bring further production and extend this period. But there is a need to build up alternative sustainable energy production while there is still time. In *A visionary Danish energy policy 2025* the Danish Government presented a vision for the long-term phasing-out of fossil fuels such as coal, oil and gas, and appointed the Climate Commission to set out specific directions for how this can be done. A phasing-out of fossil fuels will strengthen long-term supply reliability and contribute to a reduction in CO_2 emissions.

1.B. ENERGY POLICY OBJECTIVES

A visionary Danish energy policy 2025 was published in January 2007. It was followed by the *Energy Policy Agreement of 21 February 2008* between the Danish Government and all of the parliamentary parties with the exception of the Red-Green Alliance. This Agreement sets out ambitious goals for the development of renewable energy and for energy savings. A specific goal is that, compared to 2006, gross energy consumption should be reduced by 2% by 2011 and by 4% by 2020. Furthermore, renewable energy should cover at least 20% of Denmark's gross energy consumption in 2011.

In order to achieve these goals, the *Energy Policy Agreement of 21 February 2008* contains a number of resolutions on, among other things, improving the feed-in tariff for electricity from new wind turbines, biomass incineration, biomass gasification, and biogas. Funding was allocated to promote the introduction to the market of newly developed renewable energy technologies such as solar cells, thermal gasification of biomass, and wave power, and government support for the research, development and demonstration of energy technologies will be increased to DKK 1 billion in 2010.

The Agreement also contains a range of initiatives aimed at promoting local acceptance of and commitment to new onshore wind turbine projects. Neighbours will be entitled to seek compensation for loss of property value due to the erection of wind turbines. A local option to purchase has been introduced for new wind turbine projects. Local wind turbine owners' associations can apply for a guarantee covering their financing of essential preliminary investigations. And municipalities where new wind turbine projects are established will have access to subsidies from a green scheme for new wind turbine projects.

The *agreement of 21 February 2008* also includes initiatives to further promote the development of wind power. A follow-up to the 2004 scrapping scheme for old wind turbines was agreed. And it was also decided that the Danish Minister for the Environment should conclude an agreement on behalf of the Danish Government with Local Government Denmark with a view to facilitating local wind turbine planning. In April 2008 the Minister duly signed just such an agreement with Local Government Denmark setting out the goals for local planning of onshore wind turbines. In connection with this, the Danish Ministry of the Environment's Wind Turbine Secretariat was established to assist the municipalities with their planning.

Finally, the supporting parliamentary parties agreed that 400 MW of new offshore wind turbine capacity should be established and operational by the end of 2012.

1.C. EU ENERGY AND CLIMATE POLICY

The aims of the EU as a whole are for emissions of greenhouse gases to be reduced by 20% compared to the 1990 level, for renewable energy to constitute at least 20% of energy consumption (and at least 10% in the transport sector), and for energy efficiency to be improved by at least 20%, all by 2020: the so-called "20-20-20 in 2020".

The obligations to develop renewable energy are spread throughout the 27 Member States according to a range of criteria. Denmark must improve its development of renewable energy so that it can cover 30% of energy consumption in 2020. It is a matter for the Member States themselves to choose the renewable energy technologies that best suit their local energy resources and energy systems. In Denmark, biomass (including waste) and wind power are expected to be the chief renewable energy sources leading up to 2020.

1.D. WIND POWER – A CHALLENGING SOLUTION

The Danish climate makes wind power one of the most obvious renewable energy sources because the wind conditions are more favourable for electricity production than in most other European countries. Added to this, since the end of the 1970s Denmark has been building up a strong technological and research competence within wind power, and wind turbines have undergone such considerable technological advances that wind has become one of the most competitive renewable energy sources. In 2008 the combined global market share of the two largest Danish wind turbine manufacturers was just over 27%.

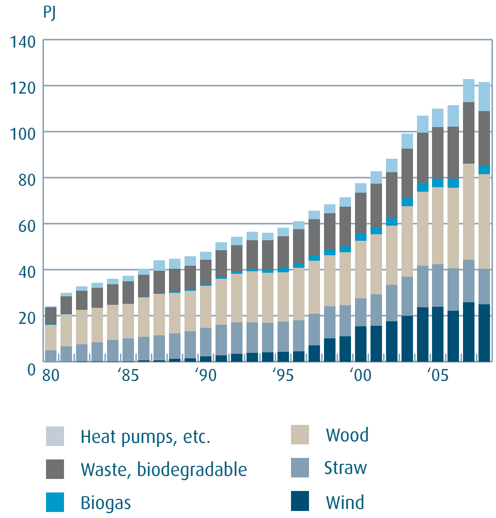
However, although wind turbines can thus be regarded as an important part of the solution to Denmark's obligations, wind power is also a technology that presents certain social challenges. Even though wind turbines have undergone considerable technological advances, it is still more costly to produce electricity with wind turbines than with conventional thermal power plants, especially all the while that the external environmental costs of conventional electricity production are not fully incorporated into the market price. In accordance with the applicable regulations, the additional costs of producing electricity with wind turbines are paid for by the electricity consumers as a public service obligation (PSO) that is collected through their electricity bills.

In comparison with fuel-fired power plants, electricity production from wind turbines is also more unstable because wind turbines do not produce electricity at low wind speeds (less than 4 metres per second) or high wind speeds (more than 25 metres per second). Under average wind conditions, an onshore wind turbine can produce electricity for 6,000-7,000 hours a year, corresponding to 70-80% of the total hours in the year. But the production fluctuates with the wind speed. This presents special challenges for the electricity system in incorporating the varying electricity production, and it is necessary for the system to operate with a reserve capacity in the form of power plants or cross-border connections in order to be able to cover the Danish electricity requirement in periods when the wind turbines are idle. Furthermore, work is being carried out to improve the incorporation of wind power, among other forms, by making the individual turbines easier to regulate. And the possibilities of using intelligent electricity meters, electric cars and heat pumps are being investigated.

Wind turbines erected onshore are often highly visible in the landscape. This is particularly true of the latest MW wind turbines, which have rotating blades that reach more than 125 metres high. Although new wind turbines have been designed to minimise noise nuisance, the turbines can still be both seen and heard in the immediate surroundings, which means that restrictions on distance to neighbours are imposed and the municipalities are obliged to consider the landscape in the planning that underpins the siting of new wind turbines. As a result of the ambitious objective for renewable energy, the Danish Government is seeking to promote the erection of new, more efficient wind turbines both offshore and onshore.

Photo: Wind Turbine Secretariat

FIGURE 1.1. PRODUCTION OF RENEWABLE ENERGY



Source: Danish Energy Agency

The production of renewable energy in 2008 was calculated at 121.5 PJ, which was 1.4 PJ less than the year before. In 2008, the production of wind power fell by 0.9 PJ to 24.9 PJ due to poor wind conditions. Under the Energy Policy Agreement of 2008, renewable energy should cover at least 20% of gross energy consumption in 2011.

2. THE HISTORY OF DANISH WIND POWER

FIGURE 2.1
TECHNICAL SPECIFICATIONS OF A V90 NACELLE

Illustration: Vestas Wind Systems A/S

1. Oil cooler
2. Water cooler for generator
3. High voltage transformer
4. Ultrasonic wind sensors
5. VMP-Top controller with converter
6. Service crane
7. OptiSpeed® generator
8. Composite disc coupling
9. Yaw gears
10. Gearbox
11. Mechanical disc brake
12. Machine foundation
13. Blade bearing
14. Blade hub
15. Blade

2.A. HOW A WIND TURBINE IS CONSTRUCTED

A wind turbine is a machine that converts the kinetic energy of wind into electricity. The idea of taking energy from wind has been known and exploited for centuries in many countries. In Denmark, wind power has historically been used to produce mechanical energy for, among other things, grinding corn.

The size of a wind turbine can be stated in several ways. It can be the wind turbine's maximum electrical output, its height from the ground to the top of the blade tip, the blade's diameter, or the area that the rotor's three blades cover in one revolution. By way of example, we might have a wind turbine of 1 MW (1,000 kW), a total height of 77 metres, a swept area (rotor diameter) of 54 metres, and a rotor area of 2,300 square metres.

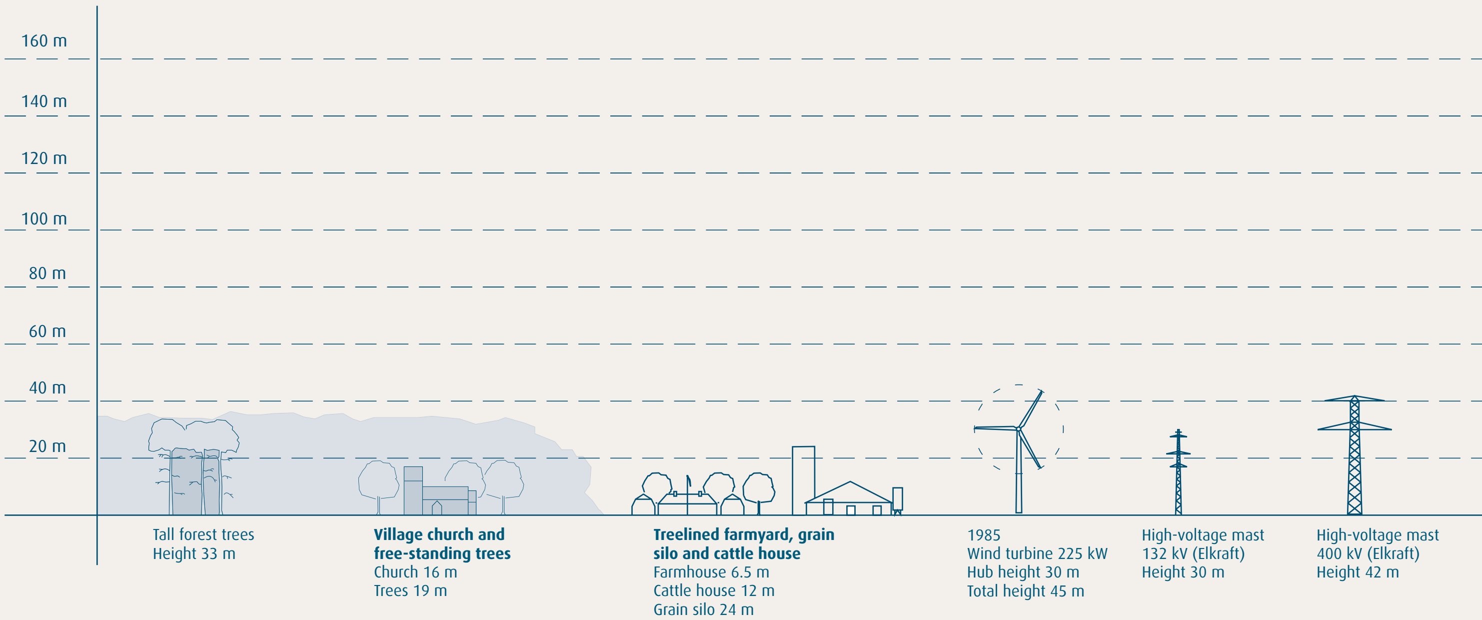
A modern wind turbine consists of a rotor (the Danish design has three blades) that drives a generator that produces electricity. The rotor and generator are installed at the top of a tower, which stands on a foundation in the ground or in the seabed. The turbine cap (nacelle) and the blades are controlled based on measurements of the wind direction and speed. In order to ensure the best possible incorporation of the wind turbine's production into the electricity system, new wind turbines are fitted with advanced control electronics, and a modern wind turbine consists of up to 10,000 different components.

2.B. WIND TURBINE ELECTRICITY PRODUCTION

In simple terms, a wind turbine not only utilises the wind's pressure on an obliquely positioned blade, but also utilises the fact that the air current around the blade creates a negative pressure on the rear of the blade in relation to the wind. The force from this negative pressure produces a draught that causes the blades to rotate.

The electricity production of a wind turbine depends on wind conditions. Obviously the wind does not blow constantly, and wind speed varies greatly from place to place and over time. On average, the wind blows more at sea than on land. In Denmark, it blows most along the western and southern facing coasts and least inland. A turbine on the west coast of Jutland generally therefore produces twice as

WIND TURBINE SIZES



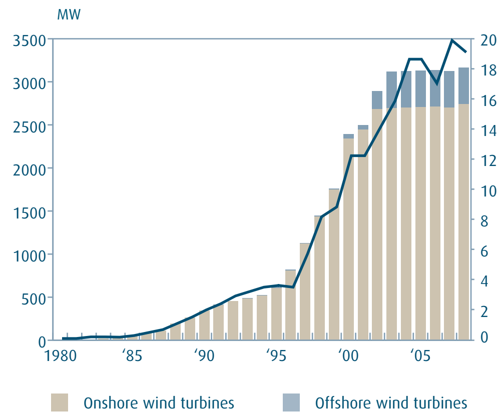
much as a turbine of the same size located on an unwindy point inland. Future wind turbines will generally be of megawatt scale. And as future turbines will be far more efficient, significantly fewer turbines will be needed for electricity production.

The electrical output of a wind turbine is measured in kW or MW (1,000 kW), while the production volume is measured in kWh or MWh. The maximum output that a wind turbine can produce is referred to as the rated output or, in popular terms, the turbine size. A wind turbine of 2 MW can thus produce a maximum output of 2 MW, typically at wind speeds of 15-25 metres per second. At maximum production, the turbine produces 2 MWh (2,000 kWh) in one hour, equivalent to half of an average Danish family's annual electricity consumption. Or, to put it another way, a 2 MW wind turbine can produce electricity for around 1,000 electric kettles with an output of 2 kW switched on at the same time.

The majority of wind turbines are designed so that they start producing electricity at a wind speed of 4 metres per second and reach their maximum production volume at wind speeds of 12-15 metres per second. For safety reasons, the wind turbines stop running if the wind speed exceeds 25 metres per second. The wind meter on the individual turbine informs the turbine's control system when the wind speed is sufficient to make electricity production worthwhile (4 metres per second) or when the wind becomes too strong. In the latter case, when the wind drops so that it is safe to start producing again, the control system is informed so that the turbine can be restarted. For safety reasons, a wind turbine is fitted with two independent braking systems, at least one of which must be aerodynamic.

A new large onshore wind turbine sited where there are good wind conditions will typically produce at maximum output for around 2,500 hours a year. In an average wind year, this type of wind turbine will be able to produce around 5,000 MWh, equivalent to the annual electricity consumption of 1,250 single-family homes with an electricity consumption of 4,000 kWh. An offshore wind turbine will typically be able to produce 3,000-4,000 hours a year at maximum output; most for locations in the North Sea, less in the Baltic region and internal Danish waters.

FIGURE 2.2
WIND CAPACITY AND SHARE OF ELECTRICITY SUPPLY



Source: Danish Energy Agency

The use of wind power increased greatly in the second half of the 1990s, reaching around 15% of the overall electricity supply in 2000. Since then, the share of wind power has further increased to around 19%. The total wind power output, which exceeds 3,000 MW, is produced by just over 5,000 wind turbines.

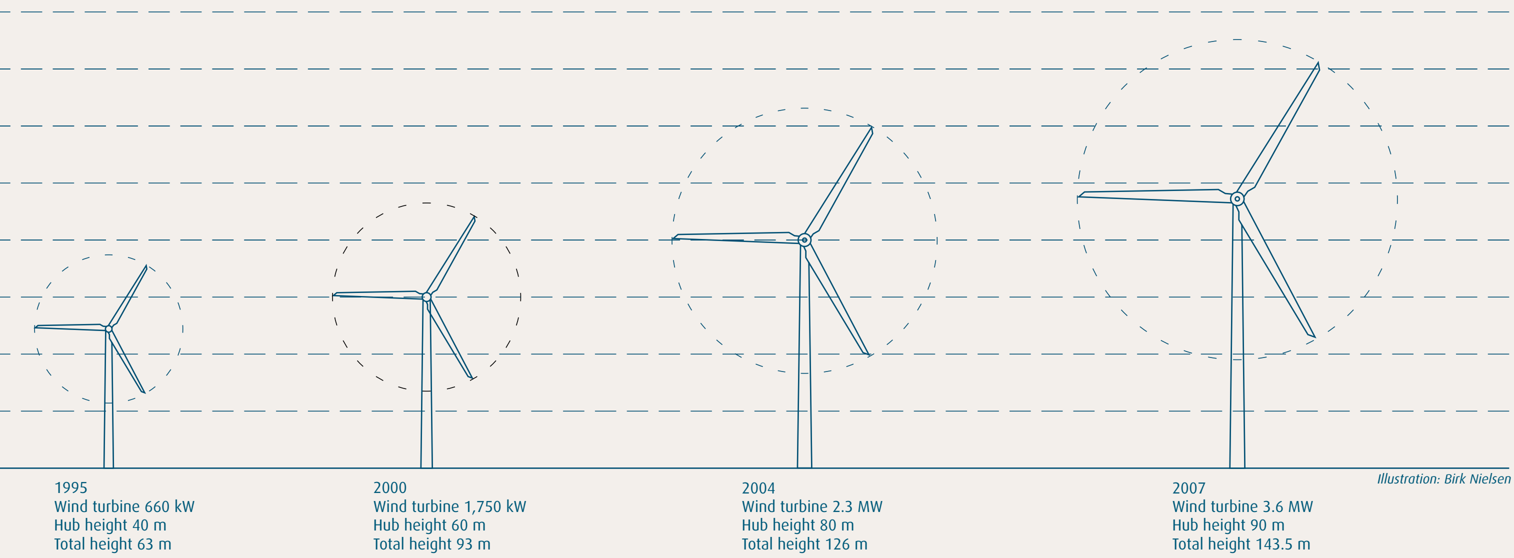


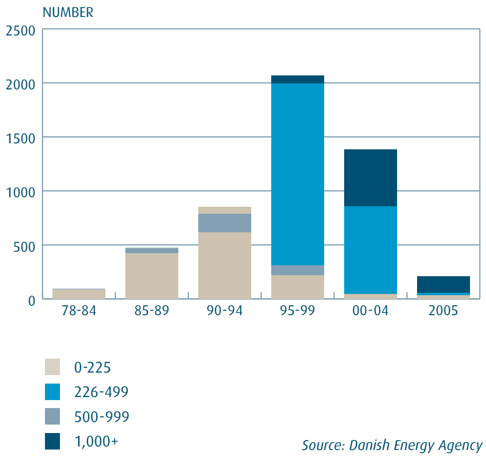
Illustration: Birk Nielsen

FIGURE 2.3 BREAKDOWN OF EXISTING TURBINES BY OUTPUT AND INSTALLATION YEAR

Period	0-225 kW	226-499 kW	500-999 kW	1,000+ kW	Total
78-84	91	1	0	0	92
85-89	425	43	6	0	474
90-94	616	169	65	0	850
95-99	218	91	1687	73	2069
00-04	44	2	812	526	1384
05-09	33	0	26	150	209
Total	**1427**	**306**	**2596**	**749**	**5078**

Source: Danish Energy Agency

FIGURE 2.3 BREAKDOWN OF EXISTING TURBINES BY OUTPUT AND INSTALLATION YEAR



Source: Danish Energy Agency

Danish wind turbines have undergone considerable upscaling. Up to the mid-1990s, the majority of wind turbines that were erected had an output of 225 kW or less, and a large proportion of these have since been replaced by fewer, larger wind turbines under the "scrapping schemes". Most of the wind turbines erected in the last decade have had an output above 500 kW. The largest new Danish wind turbines have an output of 3.0-3.6 MW.

2.C. THE DEVELOPMENT OF DANISH WIND TURBINES

The first batch-produced Danish wind turbines from the late-1970s had an output of 22 kW, and the wind turbines were gradually scaled up to 55, 75 and 95 kW through the course of the 1980s. Alongside this commercial production, a government-funded development programme was undertaken by the electricity companies to test considerably larger pilot wind turbines. Since the 1980s, the wind turbine industry's commercial products have become increasingly larger-scale, and the largest commercial wind turbines produced by Danish manufacturers today are 3 MW (Vestas) and 3.6 MW (Siemens Wind Power) respectively.

The 3.6 MW wind turbine has a rotor diameter of 107 metres, a swept area of 9,000 square metres, and a hub height of 80-100 metres depending on the conditions at the erection site. The 3.6 MW wind turbine can thus reach a total height of more than 150 metres and a weight of around 465 tons.

The number of wind turbines in Denmark peaked in 2000 at more than 6,200, of which more than half were older wind turbines with an electrical output of less than 500 kW. Since then, the number of wind turbines has decreased by around 1,000, while the total installed output has grown from just under 2,400 MW in 2000 to just under 3,400 MW end of 2009. In the same year, smaller wind turbines with an output of less than 500 kW accounted for around 11% of the total installed output.

The wind power share of the domestic electricity supply has been growing steadily since 1980. In 1990, the share was 1.9%, and since then it has increased sharply. In 1999 the figure topped 10%, and in 2008 it reached 19.1% of the electricity supply. In *A visionary Danish energy policy 2025* from 2007 the Danish Government formulated an objective of more wind power through strategic planning of wind turbine development. This includes a good framework for Danish wind capacity and the promotion of onshore and offshore demonstration and pilot sites as well as the drafting of an infrastructure plan for offshore wind turbines.

In 2008, the wind turbine industry's Danish production sites had a gross turnover of DKK 53 billion, and overall exports reached DKK 42 billion, equivalent to 7.2% of total Danish exports. The wind turbine sector had 28,400 employees at the end of 2008.

2.D. PUBLIC INVOLVEMENT

The development of wind power in Denmark has been characterised by strong public involvement. It was small machinery manufacturers that created the established wind turbine industry, and only after the consolidation of the industry through the 1990s did it become dominated by large, partly internationally owned and listed companies. Similarly, on the customer side numerous joint-owned wind turbines were established in the period 1984-94. Around two thousand of the 5,200 Danish wind turbines are still owned by local wind turbine owners' associations. These are mostly older, smaller wind turbines because the majority of wind turbines erected since 1995 are owned by individuals, energy companies and other commercial wind power companies.

The progression towards fewer joint-owned and relatively large wind turbines has made it difficult to maintain local support for new wind power projects. But to ensure continued development of wind power, it is essential to have backing in the local community. The *Energy Policy Agreement of 21 February 2008* therefore stipulated that a range of new initiatives should be undertaken to promote local acceptance and option to purchase wind turbines shares of new wind power projects. The regulations are examined in more detail in section 6.

3. WIND TURBINES AND THEIR SURROUNDINGS

3.A. ENVIRONMENTAL FEATURES OF WIND TURBINES

CLIMATE AND AIR POLLUTION

Wind power is regarded as an environmentally renewable energy source because producing electricity with wind turbines does not entail the use of fossil fuels such as oil, natural gas and coal. In terms of energy supply, wind power is advantageous because the source of the electricity production, i.e. wind, is renewable and the electricity from wind turbines is not therefore conditional on the import of fuels or the use of limited resources. In terms of the environment and climate, wind power has major benefits because it is not associated with atmospheric emissions of CO_2, SO_2, NO_x and particles, as is the case to a greater or lesser extent with power plants that use fossil fuels.

Emissions of SO_2, NO_x and particles pollute the regional and local environment around the power plants, while emissions of CO_2 from electricity production are regarded as the largest global contributor to the greenhouse effect, which is considered by the UN's Intergovermental Panel on Climate Change (IPCC) to be a serious threat to the climate. "Greenhouse effect" is a term that denotes the changed balance between incoming solar radiation and heat radiated out into space, which arises due to human-created discharges of greenhouse gases such as CO_2, methane and nitrous oxide.

ENERGY BALANCE

The energy balance of wind turbines over their lifetime is analysed using a life cycle assessment (LCA) that covers energy consumption and other effects of production, erection, ongoing operation, and scrapping when the wind turbine no longer can or needs to produce electricity. In this assessment, raw materials for the wind turbine's components as well as energy consumption for production, transport, operation and disposal are incorporated as a negative impact on the environment. The positive side includes the wind turbine's overall electricity production and any recyclable materials. Assessed over the wind turbine's normal lifetime of 20-25 years, the negative environmental impact is minimal compared with the average European electricity production. Over 20-25 years the wind turbine will typically produce more than 35 times the energy production involved in its manufacture, operation, etc. A modern MW wind turbine will take around seven months to produce the amount of energy used in its manufacture, erection, operation and disposal.

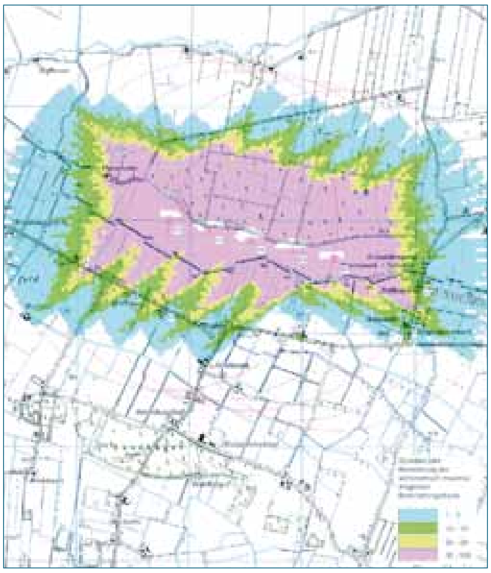
3.B. IMPACT ON THE IMMEDIATE SURROUNDINGS

The planning and environmental legislation sets out requirements to ensure that a wind turbine project will not cause major damage or nuisance to its surroundings, including noise and spacing requirements. It is also assumed that as a rule an environmental impact assessment (EIA) will be carried out as part of the detailed planning for specific projects. As well as describing the environmental impacts, this ensures, among other things, that the legislative requirements are observed. The overall impact of wind turbines on their immediate environment includes visual impact, noise, shadow, the effects of lighting, impacts on nature, etc. The nature of these impacts depends on how the wind turbine is positioned in the landscape, the type of landscape, the wind turbine's size, and proximity to the wind turbine. In order to minimise the overall impact, when planning the siting of wind turbines the municipalities should seek to limit these nuisances, including ensuring that noise and spacing requirements are observed. Similarly, wind turbine manufacturers are continuously working to optimise turbine design so that they not only produce optimally but also reduce the impact on their surroundings as much as possible.

SHADOW

A wind turbine casts shadows when the sun is shining. In windy, sunny weather, an area of the turbine's surroundings will be affected by rotating shadows from the blades. In Denmark the area lying to the south of the wind turbine will never be affected by shadow from the blades. Nuisance from shadow, which takes the form of a rapid change between direct light and short "flickers" of shadow, depends on

Photo: Wind Turbine Secretariat



IllIllustration: Odense Environment Centre, based on calculations from CUBE Engineering

FIGURE 3.1.
SHADOW CHART IN THE EIA

In new wind turbine projects, the project developer must provide information in an Environmental Impact Assessment (EIA) on the shadow cast by wind turbines. The chart shows the area of calculated shadow for "real case" (weather-dependent) in relation to Danish neighbours in an alternative project involving 5 x 3 MW wind turbines at Rens Hovedgaard Plantage in Aabenraa Municipality. Number of hours per year.

Photo: Wind Turbine Secretariat

Photo: Wind Turbine Secretariat

Factbox

SHADOW

Shadows cast by rotating turbine blades are experienced by neighbours as a nuisance, with the shadows passing across their homes for a short duration but at a high frequency. The applicable spacing requirements ensure that neighbours are mainly subjected to shadows in the early morning and late evening. Shadow is normally calculated as "real case", i.e. taking into consideration the normal distribution of sunshine hours and wind. Possible remedial measures include switching off the wind turbines at critical times.

where the wind turbine is standing from the perspective of the neighbour, the distance between the wind turbine and the neighbour, the wind turbine's hub height, and the length of the blades.

The critical times for shadow occur mainly in the early morning and late evening, with long shadows at a greater distance from the wind turbines than the neighbour distance requirement of four times the total height of the wind turbine. The impact of shadow is calculated as the total number of hours annually that a neighbour is subjected to shadow and will vary with seasonal changes in the weather. The assessment of the anticipated number of annual hours of shadow is therefore calculated based on the anticipated normal distribution of operating hours and sunshine hours during the course of the year.

It is recommended that the calculated normal distribution of shadow hours for neighbours not exceeds 10 hours a year. By taking these issues into consideration in the planning of wind turbine sitings, the periods during which shadow actually occurs can be limited. If a full assessment shows that the most suitable siting entails that the recommended maximum of 10 hours' shadow cannot be observed, the owner of the wind turbine may alternatively be required to shut down the wind turbine in critical periods. The wind turbines can be fitted with meters so that the operation can be halted if the sun shines during critical periods; this can reduce operating losses.

REFLECTION

As wind turbine blades must have a smooth surface to be able to produce optimally and repel dirt, the blades can produce reflective flashes. As part of the type-approval of wind turbines, the reflective qualities of the blades are stated. Typically, the reflective effect of the blades will be halved during the wind turbine's first year of operation, and in their planning the municipalities can set requirements for anti-reflective treatment of the blades. Normally, the blades from the manufacturer will be surface-coated to obtain a low gloss. Usually the gloss value will be less than 30, which is regarded as sufficiently low for reflections from the wind turbine not to be a problem.

MARKING OF WIND TURBINES IN RELATION TO AIR TRAFFIC

In order that installations should not compromise the safety of air traffic, any obstacles – including wind turbines – with a total height of more than 100 metres must be approved by Civil Aviation Administration-Denmark (CAA-Denmark). Around state-approved airports and airfields, aircraft are protected against obstructions using the approved obstacle limitation surfaces. The approach plan's height restrictions are registered with easements or notified in the municipal plans.

All wind turbines with a total height of minimum 150 metres must be provided with high-intensity, white flashing lights. The exact regulations are set out in the *BL 3-10 Regulations for Civil Aviation* based on applicable international standards and recommendations. The basis for the regulations is a desire for obstructions to air traffic to be visible at a suitable distance so that the pilot can take the necessary operational actions in time. In the case of wind turbines of 100-150 metres in height, which will typically be pertinent in connection with projects under the scrapping scheme and new onshore wind turbines, CAA-Denmark will carry out a specific assessment of the need for marking, including taking into consideration Danish Defence's assessments of military flights in the area. Under normal circumstances, the marking of the wind turbines with low-intensity fixed red obstruction lights on the nacelle plus painting the wind turbine white will be sufficient. Where special air safety factors apply, marking with medium-intensity flashing obstruction lights will be necessary in addition to painting the wind turbine white. It would be appropriate for requirements for air traffic marking to be clarified with CAA-Denmark before an EIA, where one is required, is drawn up.

Previous attempts to counteract light nuisance from TV-station transmitting masts have shown that it is not possible to effectively shield surrounding houses against obstruction lights. Any shielding must be carried out taking into consideration that obstruction lights must be observable by the pilot from all directions in the horizontal plane.

3.C. NOISE

Wind turbines emit a relatively weak but characteristic noise. The noise emanates from the operation of the turbine's gear and generator as well as from the movement of the blades through the air. In relation to generated output, modern wind turbines emit considerably less noise than the earliest wind turbines from the 1970s and 1980s. In particular, the mechanical noise from the turbine's gear and generator are significantly reduced in comparison with earlier models. In modern wind turbines, the machine house is soundproofed, the generator and gear are suspended in rubber elements, and the nacelle's cabin is tight-closing and fitted with sound locks that dampen airborne noise. Blade design has developed so that the noise from the movement of the blades through the air is minimised.

In order for a wind turbine to be certified for erection in Denmark, it must satisfy a number of requirements set out in the *Danish Ministry of the Environment Order on noise from wind turbines* (no. 1518 of 14 December 2006). Among other things, a noise survey must be carried out and the noise level calculated at the premises of immediate neighbours.

Sound is measured in decibels (dB). The human ear can just detect a change in sound intensity of 1-2 dB. If the sound intensity increases by 6-10 dB, it will be heard as a doubling of the sound intensity. Similarly, a reduction of 6-10 dB will be heard as a halving of the sound intensity. The intensity of the sound is generally measured using a method that mimics the ear's sensitivity and is stated by the measuring unit decibel-A, dB(A).

In accordance with the Danish Ministry of the Environment's Order, the noise in the open land immediately outside the neighbour's house and in open spaces up to 15 metres from the house may not exceed 44 dB(A) at a wind speed of 8 metres per second. This corresponds roughly to the noise of soft speech. In more densely built-up areas, summer home areas and noise-sensitive recreational areas, the noise may not exceed 39 dB(A). The limits are lower for lower wind speeds. The municipalities monitor compliance with these noise limits.

The relatively weak noise from wind turbines also includes some low-frequency noise, i.e. deep sound with a low frequency. Low-frequency noise is where a significant proportion of the sound energy is found in the frequency range below around 160 Hertz (Hz). Hertz is a designation for the number of oscillations per second. None of the noise surveys that have been carried out suggest that there are special problems with low-frequency noise from wind turbines. In the assessment of the Danish Environmental Protection Agency, wind turbines that observe the limits for ordinary noise do not give low-frequency noise higher than the recommended limit. In order to shed further light on the issues of low-frequency noise, thereby giving municipalities and players in the wind power industry a more reliable basis for evaluating new wind turbine projects, DELTA – Danish Electronics, Light and Acoustics – has headed up a research project that has been mapping the issues of low-frequency noise from modern wind turbines since 2006. The project is expected to be completed in spring 2010.

Infrasound is sound with a frequency lower than 20 Hz and thus constitutes the "deepest" part of the low-frequency range. Previously it was thought that infrasound could not be detected by the human ear, but infrasound can actually be heard if it is strong enough, and even weak infrasound is regarded as a nuisance. The threshold for hearing infrasound has been well researched, and the Danish Environmental Protection Agency recommends a limit that is 10 dB lower than the hearing threshold. The infrasound emitted by modern wind turbines is of no consequence for the surroundings and is much weaker than the Danish Environmental Protection Agency's recommended limit.

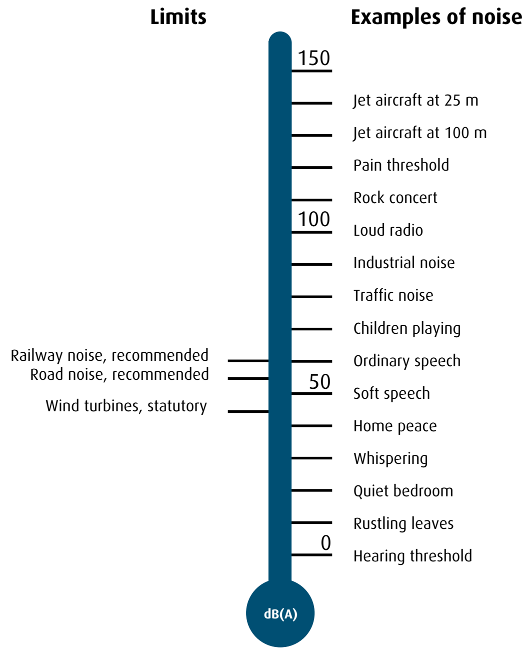


Illustration: Factsheet from the Danish Wind Turbine Owners' Association

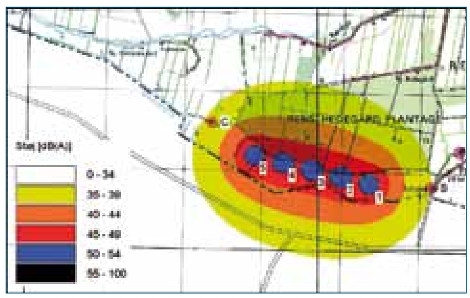


Illustration: Odense Environment Centre, based on calculations from EMD International

FIGURE 3.2
CHART OF CALCULATED NOISE ZONES IN THE ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

The two charts from the EIA for the wind turbine project at Rens Hovedgaard Plantage show the calculated noise zones for Danish neighbours from 5 x 1.8 MW wind turbines. The chart on the left shows noise zones at a wind speed of 6 metres per second, while the chart on the right shows the same noise zones for a wind speed of 8 metres per second. The noise level is stated in dB(A). The colours indicate the noise level: the darker the colour, the higher the noise level.

4. ONSHORE WIND TURBINES

Factbox

WIND TURBINE PLANNING PHASES

A typical planning process passes through the following steps:

Designation of wind turbine areas

- Consideration of potential areas, process and political aims in the municipality

- Idea phase and scoping
  - Invitation to submit ideas and proposals
  - Consultation with relevant authorities
  - Citizen meeting, where required
- Processing of any comments and consultation responses received
- Drafting of proposed municipal plan, including acceptance and rejection of alternatives, based among other things on a general environmental assessment of the plan and political aims
- Drafting of an environmental report summarising the general environmental assessment of the plan

- Public phase
  - Announcement of proposed municipal plan and environmental report
  - Citizen meeting, where required
- Processing of objections and comments received
- Any necessary revision, plus consultation period and any new public phase
- Final adoption of the plan
- Period for complaints

Planning for a specific wind turbine project

- Application for a specific project by a project sponsor in the designated wind turbine area
- Decision on whether an EIA is required

- Idea phase and scoping
  - Invitation to submit ideas and proposals
  - Consultation with relevant authorities
- Citizen meeting, where required

Photo: Birk Nielsen

The perception of order is a basic aesthetic precondition. It is therefore recommended that wind turbines should be erected in geometric (usually linear) formations that create a contrast with the landscape. The photo shows the visualisation for Lønborg Hede.

4.A. POLITICAL FRAMEWORK CONDITIONS FOR THE DEVELOPMENT OF WIND TURBINES

The political framework conditions for the erection of onshore wind turbines have been agreed in part in the *Energy Policy Agreement of 21 February 2008* and subsequently implemented in the *Danish Promotion of Renewable Energy Act,* which was adopted by the Danish Parliament in December 2008 and entered into force on 1 January 2009. The municipalities are responsible for securing the necessary planning basis for wind turbines with a total height of up to 150 metres in the form of designated wind turbine areas with associated guidelines in the municipal plan as well as supplements to the municipal plans with associated EIAs and local plans for the specific wind turbine projects under application. In the case of wind turbines over 150 metres, the Environment Centres within the Danish Ministry of the Environment are the planning authority. The Environment Centres are also tasked with monitoring that the municipalities plan for wind turbines in accordance with government interests.

As part of the objective for renewable energy to constitute 20% of gross energy consumption in 2011, the Danish Government entered into an agreement with Local Government Denmark that the municipalities, through their planning, should reserve areas that can accommodate onshore wind turbines with a total output of 150 MW; 75 MW in each of the years 2010 and 2011.

It was also agreed that the Danish Ministry of the Environment should strengthen its follow-up on the municipalities' work of implementing the scrapping scheme adopted as part of the *Energy Policy Agreement of 29 March 2004 on wind energy and decentralised combined heat and power.*

4.B. MUNICIPAL PLANNING AND REGULATIONS ON EIAS

Following the Local Government Reform, the planning authority for onshore wind turbines up to 150 metres has passed to the municipalities. The regulations for municipal planning ensure that citizens, associations, authorities and other stakeholders are continuously involved in the process. In order to be able to assist the municipalities in this work, the Danish Ministry of the Environment has set up the Wind Turbine Secretariat under the Agency for Spatial and Environmental Planning.

In order to allow enough time for drafting various materials, citizen involvement, etc., both the municipal designation of wind turbine areas and the municipality's subsequent processing of a specific project normally take at least a year.

Apart from household and small turbines, wind turbines may only be erected in areas designated through reservations and guidelines in the municipal plan. The municipality must therefore assess which areas are suitable for erecting wind turbines.

The local council must ensure in its planning that it gives full consideration to neighbouring residences, nature, the landscape, culturo-historical values, agricultural interests, and the possibility of exploiting the wind resource.

The municipal plan must include guidelines and a framework, and must be accompanied by a statement on the assumptions underlying the local council's proposed plan. The guidelines for designated wind turbine areas must include regulations on the anticipated maximum number and size of the turbines as well as the spacing between the turbines.

The further planning of specific projects then awaits the initiative of a project sponsor, a wind turbine owners' association or others wishing to use the designated area to erect wind turbines.

A project sponsor wishing to establish a wind turbine project must notify the project to the municipality. The planning process for projects requiring an EIA begins with an idea phase in which the municipality drafts a discussion paper inviting proposals from citizens on the content of the EIA and the supplement to the municipal plan. This idea phase, which is also called the pre-public phase, must last at least two weeks.

The planning must also satisfy the requirements for environmental assessment of plans and programmes, which include consultation with the relevant authorities, including neighbouring municipalities, the region and national bodies that have to grant environmental approvals to allow implementation of the physical planning, as well as any local and regional supply companies whose installations may be affected by the project.

Taking into consideration the feedback that it receives, the municipality draws up guidelines on the further local planning in a supplement to the municipal plan and determines the scope of the EIA, which the project owner and the municipality often prepare jointly. This material is sent for public consultation lasting at least eight weeks. In this public phase, property owners, neighbours, associations, authorities, etc., may submit objections, comments and alternative proposals.

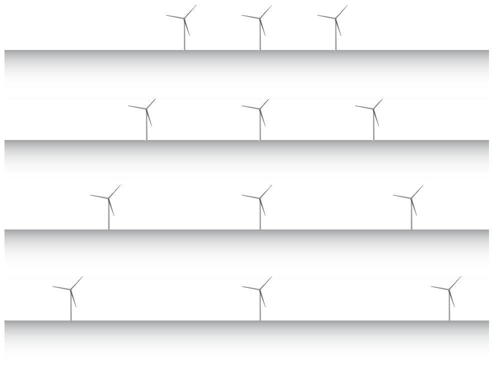
After this, the municipality can finally adopt the wind turbine project and give the project sponsor an EIA approval. If a local plan also has to be drawn up for the project, the local council draws this up in parallel. The local plan for a wind turbine area must include regulations on the turbines' exact siting, number, minimum and maximum total height, and appearance.

In accordance with the *Danish Planning Act*, a supplement to the municipal plan for a wind turbine project involving turbines with a total height of more than 80 metres or a group of more than three turbines must be accompanied by an EIA assessing the consequences of the project for the environment. Other projects are screened by the local council, which decides whether a project has such major consequences for the environment that an EIA should be drawn up or whether only a rural zone permit should be issued. *Order no. 1335 of 6 December 2006 on the assessment of certain public and private installations' impact on the environment* contains regulations on EIAs.

The EIA must assess how the wind turbine project will affect neighbouring residences in terms of, among other things, noise and shadow, nature, the landscape, culturo-historical values, and agricultural interests, as well as giving information on local wind conditions. This normally requires the project owner to draw up a visualisation of the project so that citizens can more easily form a realistic impression of the implications of the wind turbine project.

FIGURE 4.1

EXAMPLES OF SPACING IN A WIND TURBINE PROJECT



Illustrations: Birk Nielsen

With regard to both turbulence and aesthetics, it is recommended that in projects involving multiple wind turbines their spacing should be three to four times the rotor diameter. The illustrations from Birk Nielsen show examples of wind turbines spaced at intervals of two times the rotor diameter (top), three times the rotor diameter, four times the rotor diameter, and five times the rotor diameter (bottom) respectively.

- Processing of any comments and consultation responses received
- Drafting of supplement to municipal plan and local plan, including adjustment of the project based on a general environmental assessment of the plan
- Drafting of an EIA for the project

- Public phase
  - Announcement of the proposed plans, incl. EIA for the project
  - Citizen meeting, where required
- Processing of any objections and comments received
- Any revision, plus consultation period and any new public phase
- Final adoption of the plans and issuing of EIA approval
- Period for complaints

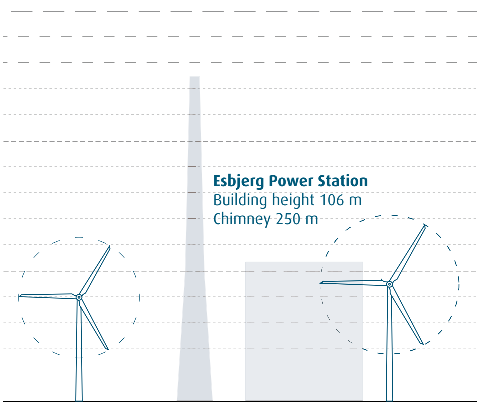


FIGURE 4.2 WIND TURBINE IN A TECHNICAL LANDSCAPE

Birk Nielsen's sketch shows the siting of MW wind turbines at Esbjerg Power Station.

Factbox

All EIAs, including those for wind turbine projects, must include:

- A description of the project.
- A summary of major alternatives to the execution of the proposed project that the project sponsor has investigated (minimum the zero alternative, i.e. the situation if the project is not implemented).
- A description of the impact of the project on people, fauna, flora, soil, water, air, climate, landscape, tangible property, and the Danish cultural heritage.
- A description of the project's short-term and long-term, direct and indirect, derived and cumulative impacts on the environment.
- A description of environment-improving measures, including preventive measures.
- A non-technical summary of the assessment.

In the case of wind turbine projects that do not require an EIA, the rural zone regulations of the *Danish Planning Act* set out requirements for informing neighbours about the project. Generally, there is no requirement for the information to include a visualisation, but Energinet.dk (the Danish transmission system operator) may require this if it would be a pre-condition for neighbours being able to realistically assess whether the project will entail a loss of value on their properties, cf. 6.b.

Decisions of the local council concerning wind turbine projects may be contested with the Nature Protection Board of Appeal.

The Danish Ministry of the Environment's Wind Turbine Secretariat is a type of "flying squad" that provides the municipalities with guidance and practical help in wind turbine planning – such as identifying the sites that are most suitable in respect of neighbours and nature protection interests, formulating idea proposals, decision-making documentation and proposals for wind turbine plans, or arranging citizen meetings, etc.

Most of Denmark's municipalities are in dialogue with the Wind Turbine Secretariat, either to get answers to specific questions or to obtain formal assistance with the planning process. The Wind Turbine Secretariat has a Danish website, **www.vind.mim.dk**, via the Agency for Spatial and Environmental Planning. Here you can find answers to frequently asked questions as well as tools for use in municipal wind turbine planning, including:

- A summary of essential siting considerations.
- A process line with a model of the planning process and a timeframe.
- Links, including to applicable regulations and the Agency for Spatial and Environmental Planning's spacing map.

4.C. REGULATIONS FOR SITING ONSHORE WIND TURBINES

The siting of new wind turbines is carried out on the basis of an overall balancing of various factors such as wind speed, distance to nearest neighbours, noise and shadow, other technical installations, and regard for the landscape and nature. This balancing is brought about through the municipal wind turbine planning, which directly involves affected citizens, organisations, authorities, etc. The key principles for erecting wind turbines are wind conditions, distance to neighbours, and regard for specific affected interests, e.g. nature protection areas and areas of culturo-historical interest.

The regulations for siting are set out in the *Danish Planning Act* and implemented in *Wind Turbine Circular no. 9295 of 22 May 2009*. The aim of the Circular is to ensure regard for landscape, neighbours, etc. Generally, new wind turbines must as a minimum be sited at a distance from the nearest neighbours of at least four times the wind turbine's total height.

Special consideration must be given to the coastal zone, which is defined in the *Danish Planning Act* as a three-kilometre zone along the coast throughout the country that is generally to be kept free of buildings and installations. If a municipality wants to erect wind turbines in the coastal zone, this requires special planning or functional justification, for example that there are especially favourable wind conditions along the municipality's coasts, as is the case in the West Jutland municipalities. Visualisation is an excellent method for illustrating the implications of new wind turbines for landscape and nature. Landscapes that in the past have been dominated by large technical installations will often be suitable for erecting large wind turbines because the turbines will not significantly increase the impact on the landscape. These technical installations might be CHP plants, waste incineration plants, high-voltage masts, industrial activities with tall chimneys, harbour areas with large cranes, etc. These installations are already highly visible in the landscape.

Large and uniform landscapes will also usually be suitable for erecting large wind turbines. The reason for this is that the landscape matches the large dimensions because it is often characterised by flat or evenly sloping terrain with large units of area and "landscape space".

Small-scale landscapes will often be less suitable for erecting large wind turbines. These landscapes are characterised by small hills or gentle slopes with less "landscape space", where large wind turbines would contrast starkly with the nature of the landscape.

A more exhaustive description of the impact of large wind turbines on different types of landscape can be found in the report *Store vindmøller i det åbne land – en vurdering af de landskabelige konsekvenser* (*Large wind turbines in the open countryside – an assessment of implications for the landscape*), which can be downloaded (in Danish only) from **www.blst.dk**.

The oldest wind turbines were often erected spread out in the landscape, which meant that they impacted a very large area in relation to their installed electrical output. As a starting point, the aim is to site new wind turbines in groups wherever possible so as to achieve a high installed electrical output with impact on a relatively small area. Furthermore, the municipality can require wind turbines in a group to be uniform and arranged in a simple geometric pattern, for example in a single row, so that the wind turbines create a calmer impression.
It is also important that wind turbines erected as a group should appear harmonious and uniform in design. A wind turbine is regarded as harmonious if there is a balance between tower height and rotor diameter. Generally, experience suggests that the most harmonious rotor/tower ratio for larger wind turbines is 0.9–1.35, depending on the total height. As an example, a wind turbine with a tower height of 80 metres and a rotor diameter of 100 metres, giving a total height of 130 metres, has a rotor/tower ratio of 1.25.

4.D. TECHNICAL CERTIFICATION OF WIND TURBINES

In order to help ensure that new wind turbines are safe and can be incorporated into the electricity system, a Secretariat for the Danish Wind Turbine Certification Scheme has been set up and located at Risø DTU (National Laboratory for Sustainable Energy at the Technical University of Denmark). The specific regulations are described in *Danish Energy Agency's Order no. 651 of 26 June 2008 on the technical certification scheme for the design, manufacture, installation, maintenance and servicing of wind turbines*. The secretariat has a website at **www.vindmoellegodkendelse.dk**. The technical prescriptions for the connection of wind turbines to the electricity grid can be found at **www.energinet.dk**.

4.E. HOUSEHOLD WIND TURBINES AND SMALL WIND TURBINES

A household wind turbine is normally understood to be a smaller, stand-alone turbine with a total height of less than 25 metres that is erected directly connected to existing housing in the open countryside, usually in a rural zone. Small wind turbines are normally understood to be stand-alone turbines with a rotor area of up to 1 m^2 ("micro turbines") or 1-5 m^2 ("mini turbines"). The turbine may be installed on a building.

For all turbine types the *Danish Ministry of the Environment Order on noise from wind turbines* must be respected when erecting and operating the turbines. Turbine types with a rotor area in excess of 1 m^2 are subject to the D*anish Energy Agency's Order no. 651 of 26 June 2008 on the technical certification scheme for the design, manufacture, installation, maintenance and servicing of wind turbines*. In the case of turbines with rotor area 1-5 m^2, however, only a registration notification is required.

Wind turbine projects must as a minimum be screened in accordance with the regulations of the *EIA Order*. Household and small turbines will not normally require an EIA, supplement to the municipal plan and EIA.

ERECTION OF WIND TURBINES IN RURAL ZONES

It is the task of the municipalities, as the rural zone authority, to issue rural zone permits. In this regard, the municipality must carry out

1:0.9

1:1.2

1:1.5

Illustrations: Birk Nielsen

FIGURE 4.3
TOWER/BLADE RATIOS

The ratio between a wind turbine's tower and blades (the "harmony ratio") is important for the turbine's own aesthetics. New types of large turbine have a more slender design than older models, and the tower can therefore better support long blades with a large rotor area and production capacity. The recommended harmony ratio thus depends on the size of the wind turbine. For wind turbines with a total height of less than 100 metres, the recommended rotor diameter is -/+ 10% in relation to the tower height, while for larger wind turbines with a total height of up to 150 metres, the recommended rotor diameter is between +10% and +35% in relation to the tower height.

Photo: Wind Turbine Secretariat

planning appraisals in respect of ongoing planning. Furthermore, landscape considerations and any building lines as per the *Danish Nature Protection Act* as well as any supplementary considerations regarding neighbours (view, reflection, etc.) must also be taken care of.

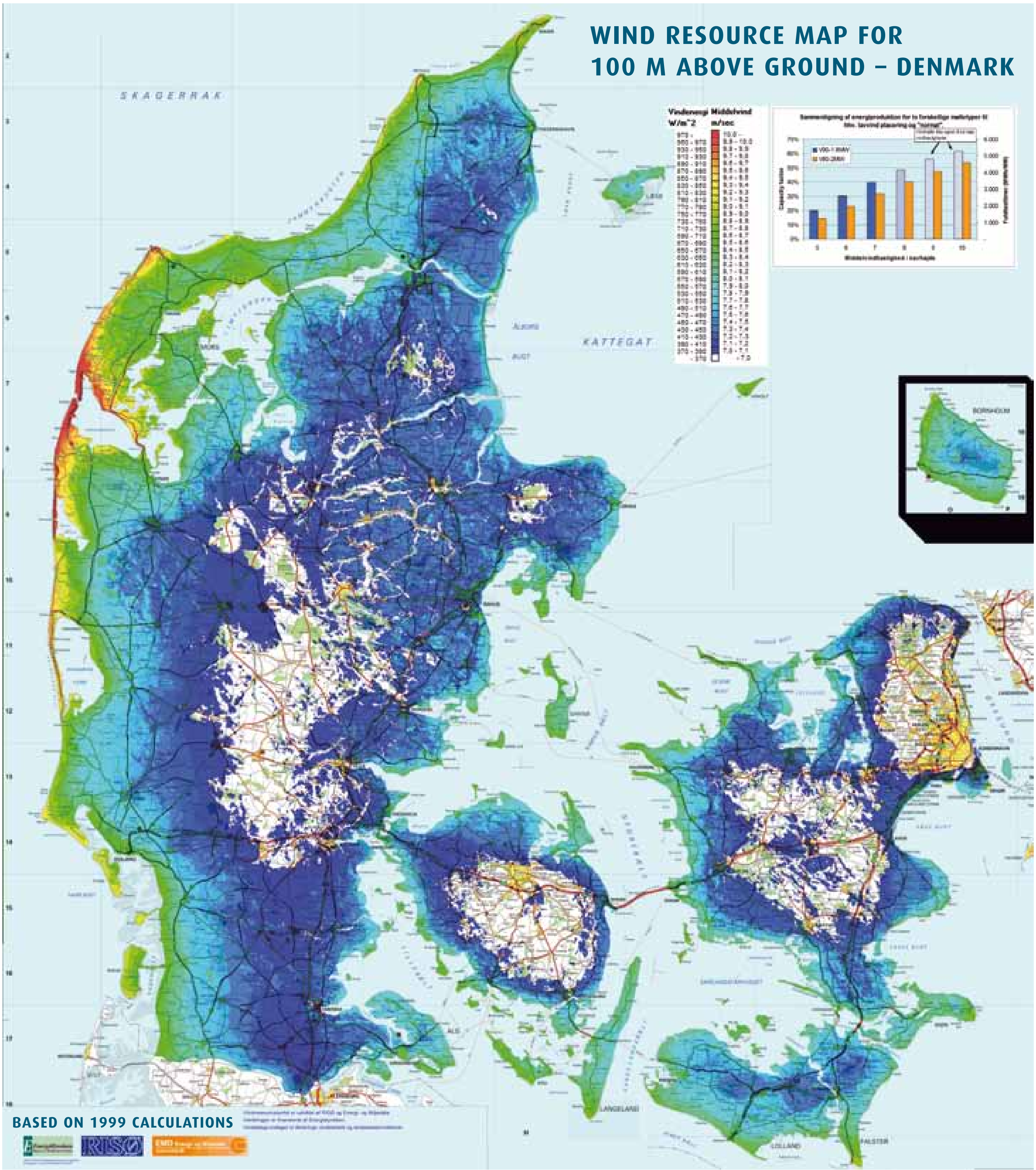
In the case of household and small turbines, the *Wind Turbine Circular* does not set out fixed requirements for the distance to neighbouring homes, etc., in relation to the turbine's total height.

The municipalities must carry out individual assessments of cases/applications. However, the fact that the decision must always be taken on the basis of a specific assessment does not preclude the municipality from clarifying in its municipal planning guidelines other protection interests and considerations that receive particular attention in its case-handling, including of course any guidelines for erecting smaller wind turbines.

WIND RESOURCE ATLAS FOR DENMARK:
In 1998, with funding from the Danish Energy Agency, Risø DTU's Wind Energy Division teamed up with the Danish software and consultancy firm EMD International to compile the Wind Resource Atlas for Denmark, which can be seen on page 17. Areas with the highest average wind speeds are shown in red and yellow, while areas with less wind are shown in green and blue.

In addition to large wind turbines, the Samsø Renewable Energy Island project has also established household wind turbines, one of which (shown below) can be seen in front of the solar-panelled roof of Samsø Energy Academy.

Photo: Samsø Energy Academy


WIND RESOURCE MAP FOR
100 M ABOVE GROUND – DENMARK
SKAGERRAK
KATTEGAT
BORNHOLM
MORS
ALS
LANGELAND
LOLLAND
FALSTER
BASED ON 1999 CALCULATIONS

5. OFFSHORE WIND TURBINES

Photo: DONG Energy

With 209 MW produced by 91 wind turbines, the Horns Rev II offshore wind farm, which was opened in September 2009, is the largest offshore wind farm in the world to date. The turbines are located 30 km from the coast and can produce electricity to cover the consumption of 200,000 households.

Photo: Samsø Energy Academy

The offshore wind farm at Paludans Flak 4 km south of Samsø comprises 10 wind turbines with a combined output of 23 MW that produce approximately 77,500 MWh a year. The offshore wind farm was commissioned in 2002, and in the long term its production will make it possible to cover electricity consumption for the operation of electric cars and hydrogen for transportation on the island. Half of the wind turbines are owned by the municipality, while the inhabitants of Samsø own most of the rest.

5.A. OFFSHORE WIND TURBINES IN DENMARK

In 1991 Denmark became the first country in the world to take wind turbines out to sea with 11 x 450 kW turbines in the Vindeby offshore wind farm. This was followed by a number of smaller demonstration projects, leading to the first two large offshore wind farms Horns Rev I and Nysted (Rødsand I) with outputs of 160 and 165 MW respectively. Some offshore wind farms have been built because power companies were given political orders to do so or via tenders, while others are wholly or partly owned by local wind turbine owners' associations such as Middelgrunden and Samsø.

With 660 MW offshore wind turbines connected to the electricity grid in 2009, Denmark is still one of the largest developers of offshore wind farms. Only the United Kingdom has a larger capacity.

In 2010 the offshore wind turbines at Rødsand II will be erected with an output of just over 200 MW. The Danish Energy Agency has tendered out another offshore wind turbine project at Anholt/Djursland with an output of around 400 MW. These projects are the result of the *Energy Policy Agreement of 29 March 2004* and the *Energy Policy Agreement of 21 February 2008* respectively.

It is considerably more expensive to build and operate offshore wind turbines than onshore wind turbines. On the other hand, the production conditions are better at sea with higher wind speeds and more stable wind conditions.

The increased costs are reflected in the feed-in tariff that the project developers for the latest offshore wind farms have obtained through the Danish Energy Agency's tender. DONG Energy, which is the project sponsor for Horns Rev II, receives DKK 0.518 per kWh for 10 TWh, corresponding to around 50,000 full-load hours, after which the electricity produced has to be sold under market conditions. E.ON AB from Sweden, which won the tender for Rødsand II, receives DKK 0.629 per kWh for 10 TWh, corresponding to around 50,000 full-load hours.

5.B. THE DANISH ENERGY AGENCY AS A ONE-STOP SHOP

The Danish Energy Agency is the authority responsible for the planning and erection of offshore wind turbines. In order to make preparation of new offshore wind turbine projects as simple as possible for project developers, the Danish Energy Agency has organised the overall official handling as a "one-stop shop", which means that a project owner wishing to establish an offshore wind turbine project only has to deal with one body – namely the Danish Energy Agency – to obtain all the necessary approvals and licences.

As a one-stop shop, the Danish Energy Agency involves other relevant authorities such as the Agency for Spatial and Environmental Planning, the Danish Maritime Authority, the Danish Maritime Safety Administration, CAA-Denmark, the Heritage Agency of Denmark, Danish Defence, etc. The Danish Energy Agency also arranges consultation with the relevant stakeholders and issues all the necessary approvals and licences. Energinet.dk is responsible for transmitting the electricity production from offshore wind turbines to the electricity grid and owns both the transformer station and the underwater cables that carry the electricity production of offshore wind farms to land.

In comparison with the official administration of offshore wind farms in other countries, the Danish model has provided a quick, cost-effective process to the benefit of operating economy in the individual projects and the development of offshore wind turbines as a whole.

5.C. MAPPING OF FUTURE SITES FOR OFFSHORE WIND FARMS

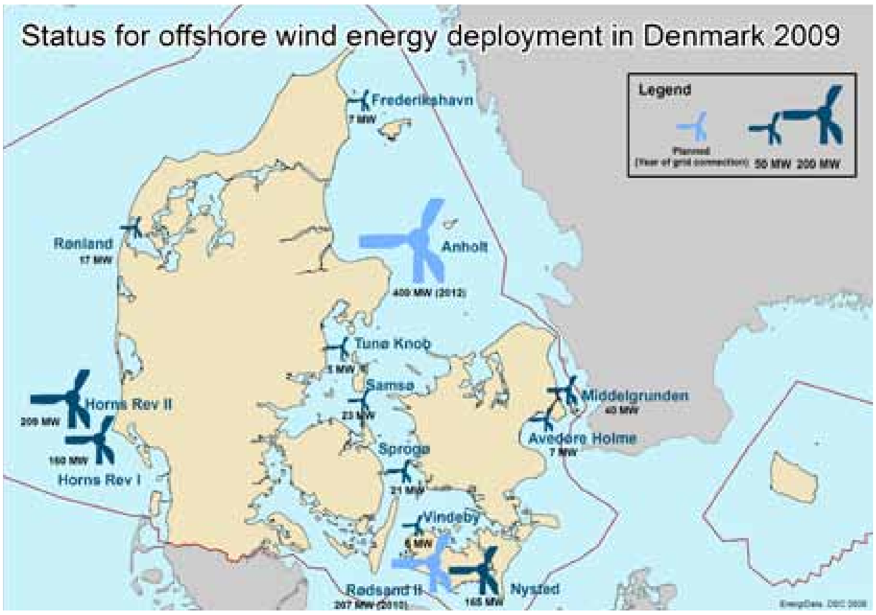
In order to ensure that the future development of offshore wind turbines does not clash with other major public interests and that the development is carried out with the most appropriate socio-economic prioritisation, the Danish Energy Agency, in conjunction with the other relevant authorities, has mapped the most suitable sites for future offshore wind farms. This mapping is a dynamic process because the framework conditions for developing offshore wind farms are continually changing. In 2007 the Danish Energy Agency published a technical mapping report designating 23 suitable sites, each with space for around 200 MW.

These possible offshore wind farms could achieve a total installed output of 4,600 MW, and with average wind speeds of around 10 metres per second they could produce around 18 TWh annually, equivalent to more than half of current Danish electricity consumption. The sites are prioritised according to public interests such as regard for grid transmission, navigation, nature, landscape, raw material extraction, and the anticipated cost of establishing and operating the offshore wind farms. The cross-ministry committee work has placed its emphasis on a planned and coordinated development of offshore wind farms and the transmission grid, and the chosen sites have been submitted to a strategic environmental assessment in order to prevent any future conflicts with environmental and natural interests.

Through its *Offshore Wind Turbine Action Plan of September 2008* the Danish Energy Agency updated the mapping in light of the *Energy Policy Agreement of 21 February 2008*. The good wind conditions at the chosen sites allow the offshore wind farms to produce for around 4,000 full-load hours a year. With sea depths of 10-35 metres and a distance to the coast of 22-45 kilometres, a balance has been struck between economic considerations and the visual impact on land.

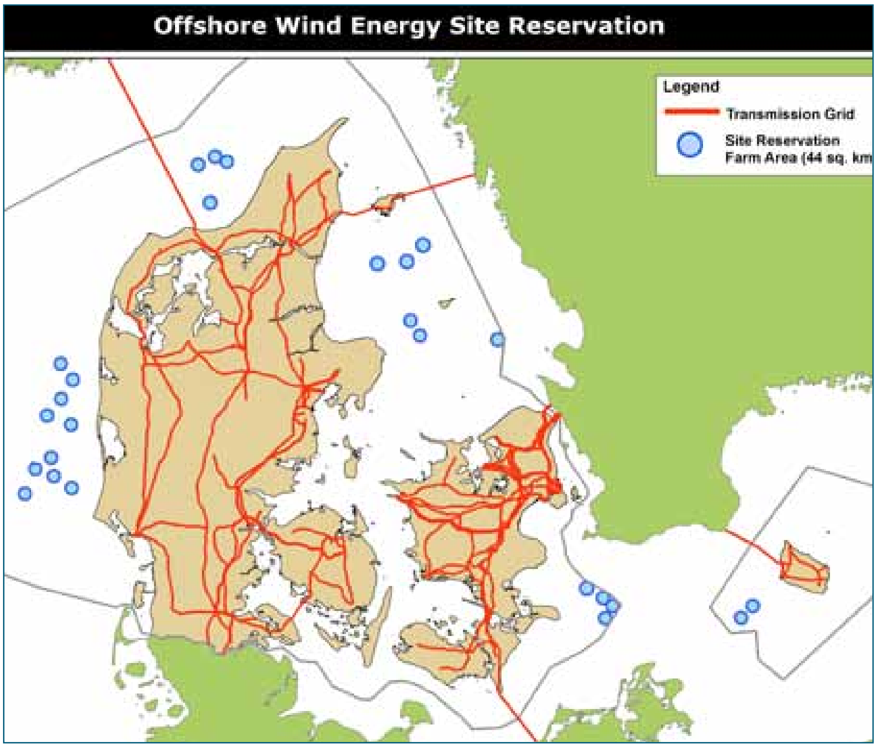
5.D. TENDERING OUT OF OFFSHORE WIND FARMS

The establishment of offshore wind turbines can follow two different procedures: a government tender procedure run by the Danish Energy Agency; or an open-door procedure. For



Map: Danish Energy Agency

The map of Denmark shows the locations of existing and planned offshore wind farms. Up to now offshore wind farms have been located with a considerable geographical spread, which has made it easier for Energinet.dk to incorporate the varying electricity production into the electricity system. Following a government tender initiated in 2009, a 400 MW offshore wind farm is to be established between Anholt and Djursland.



Map: Danish Energy Agency

The Committee for Future Offshore Wind Power Sites updated its mapping of potential locations in September 2008. The purple colour on the map indicates 26 potential sites, each of which can be developed with 200 MW, giving a total of 5,200 MW, while the existing large offshore wind farms are indicated in blue.

Photo: DONG Energy

Horns Rev II will predominantly be serviced by operating and maintenance personnel who will live for one week at a time on a habitation platform linked to the offshore wind farm. This will help reduce transport time and costs, thereby optimising operating economy.

Factbox

Two types of procedure for establishing offshore wind farms

In Denmark, new offshore wind farm projects can be established according to two different procedures: a government tender or an open-door procedure.

A government tender is carried out to realise a political decision to establish the project as part of the Danish development of renewable energy. The Danish Energy Agency tenders out the project in an open competition to obtain the lowest possible costs. Energinet.dk may be responsible for preparing the Environmental Impact Assessment (EIA) and the electricity link to land.

In an open-door procedure, the project developer applies to the Danish Energy Agency for a licence to carry out preliminary investigations and establish an offshore wind farm in the given area. The Danish Energy Agency clarifies whether there are any competing public interests and, where possible, issues the required licence. The project developer receives the same price supplement as for new onshore wind turbines and has to finance the connection of the project to the electricity grid on land.

both procedures, the project developer must obtain a licence to carry out preliminary investigations, a licence to finally establish the offshore wind turbines, a licence to exploit wind power for a given number of years, and – in the case of wind farms of more than 25 MW – an approval for electricity production.

In the government tender procedure, the Danish Energy Agency announces a tender for an offshore wind turbine project of a specific size, e.g. 200 MW, within a specifically defined geographical area. A government tender is carried out to realise a political decision to establish a new offshore wind farm at the lowest possible cost.

Depending on the nature of the project, the Danish Energy Agency invites applicants to submit a quotation for the price at which the bidders are willing to produce electricity in the form of a fixed feed-in tariff for a certain amount of produced electricity, calculated as number of full-load hours.

The winning price will differ from project to project because the result of a tender depends on the project location, the wind conditions at the site, the competitive situation in the market at the time, etc. In the two tenders so far the winning price has been higher than the feed-in tariff that is paid for an open-door project which corresponds to the feed-in tariff for new onshore wind turbines. As well as the lowest feed-in tariff, the technical and financial capacity of the bidding companies or consortia to implement the project are assessed.

Based on the experiences of the Rødsand II offshore wind farm, where the winner of the first tender ultimately chose not to implement the project due to changed market conditions, the Danish Energy Agency has tightened the conditions in the latest tenders so that the project developer has to pay a fine if the project is not implemented as planned or is delayed.

In projects covered by a government tender, Energinet.dk owns both the transformer station and the underwater cable that carries the electricity to land from the offshore wind farm. In the tender for the Anholt offshore wind farm, which is being implemented in 2009-2010, Energinet.dk will also undertake the EIA and preliminary geotechnical and geophysical surveys of the seabed. The winner of the tender will pay Energinet.dk's costs for these preliminary surveys.

In the open-door procedure, the project developer takes the initiative in establishing an offshore wind farm in a specific area. This is done by submitting an unsolicited application for a licence to carry out preliminary investigations in the given area. The application must as a minimum include a description of the project, the anticipated scope of the preliminary investigations, the size and number of turbines, and the limits of the project's geographical siting.

In an open-door project, the developer pays for the transmission of the produced electricity to land. An open-door project cannot expect to obtain approval in the areas that are designated for offshore wind farms in the report *Future Offshore Wind Power Sites – 2025* from April 2007 and the follow-up to this from September 2008.

Before the Danish Energy Agency actually begins processing an application, as part of the one-stop shop concept it initiates a hearing of other government bodies to clarify whether there are other major public interests that could block the implementation of the project. On this basis, the Danish Energy Agency decides whether the area in the application can be developed, and in the event of a positive decision it issues an approval for the applicant to carry out preliminary investigations, including an EIA.

The Danish Energy Agency has approved applications within the open-door procedure for the following offshore wind turbine projects: Avedøre Holme, involving three demonstration wind turbines (DONG Energy); Frederikshavn, involving six demonstration wind turbines (NearshoreLAB); and Sprogø, involving seven offshore wind turbines (Sund & Bælt).

5.E. IMPLEMENTATION OF AN OFFSHORE WIND TURBINE PROJECT

Once the Danish Energy Agency has granted the project developer a licence to carry out preliminary investigations, all projects follow the same procedure. The preliminary investigations include as a minimum an EIA as well as geophysical and geotechnical surveys of the seabed to clarify what type of foundation should be used.

The EIA must assess the offshore wind farm's impacts on the environment. On the basis of responses from the initial consultation of authorities and other stakeholders, the Danish Energy Agency determines what the EIA should include. The EIA must demonstrate, describe and assess the environmental consequences of implementing the project in respect of:

a) people, fauna and flora
b) seabed, water, air, climate and landscape
c) tangible property and Danish cultural heritage
d) interaction between these factors.

Furthermore, the EIA must describe proposals for alternative siting and proposals for how demonstrated environmental nuisances can be prevented or reduced. *Order no. 815 of 28 August 2000 on assessments of impacts on the environment of offshore electricity-producing installations* sets out the detailed conditions for this type of EIA.

The project developer's application to establish the offshore wind farm must include a full description of the project's expected scope, size, geographical location, coordinates for turbines, grid connection plans and cable trace, etc., as well as the results of the preliminary investigations.

Once the Danish Energy Agency has received the EIA together with a final application to establish the offshore wind farm, it sends both for public consultation with a deadline for reply of at least eight weeks. The consultation is announced on the Danish Energy Agency's website and in national and local newspapers. This gives other authorities, interested organisations and citizens the opportunity to voice objections and other comments, which the Danish Energy Agency includes in its processing of the application and the EIA.

Photo: Samsø Energy Academy

If the Danish Energy Agency does not receive any objections with weighty arguments for cancelling the project, it grants a licence to establish the offshore wind farm. In this regard, the Danish Energy Agency will generally require the project developer to document, prior to starting the construction work, a detailed project description.

The project developer must apply for a licence to exploit wind power from the offshore wind farm and, in the case of wind farms of more than 25 MW, for an authorisation to produce electricity. This must be done after the installation work has begun and at the latest two months before the first wind turbine is ready to begin operating. The offshore wind farm must not supply electricity to the grid until the licence and, where required, the approval have been granted.

Significantly and individually affected parties as well as relevant environmental organisations may appeal the Danish Energy Agency's decisions to the Energy Board of Appeal. Any appeals must be submitted in writing within four weeks of the publication of the decision.

Factbox

The environmental impact of offshore wind farms

As an integral part of the projects for the first two large demonstration offshore wind farms, Horns Rev I and Nysted, from 1996 to 2006 an Environmental Monitoring Programme was carried out to document the impact of the projects on the marine environment. On completion of the programme, at the recommendation of an international expert panel a small follow-up programme was launched focusing on the long-term effects for porpoises, water birds (common scoters, divers, long-tailed ducks, etc.) and fish.

The results show that the foundations of the offshore wind farms have created new artificial habitats, thereby contributing to increased biodiversity and better living conditions for the local fish communities. Seals were only affected in the short term during the construction work, while porpoises, which disappeared from the area while the wind farm was being built, have to some extent returned. Birds have been able to avoid the offshore wind farms.

The results of the Environmental Monitoring Programme are quality-assured by the international expert panel and regularly published on the English pages of the Danish Energy Agency's website, **www.ens.dk**.

6. NEW SCHEMES IN THE *DANISH PROMOTION OF RENEWABLE ENERGY ACT*

Photo: Visualisation by Birk Nielsen

Factbox

Claims for payment for loss of value on real property

The *Energy Policy Agreement of February 2008* introduced a scheme giving neighbours of new wind turbine projects the right to have loss of value on their property covered if the loss is assessed to be at least 1% of the property's value. The scheme was introduced to create greater local acceptance of and involvement in the erection of new onshore wind turbines.

In order for their claims to be processed, neighbours living within a distance of six times the wind turbine's total height must notify their claims for payment for loss of value within four weeks after the wind turbine project developer has conducted the prescribed information meeting. Neighbours living further away must pay a fee of DKK 4,000. If the claim for payment for loss of value is upheld, the fee is repaid.

The loss of value is assessed by an impartial valuation authority appointed by the Minister for Climate and Energy. In all there are five valuation authorities covering the whole country, each consisting of a lawyer and an expert in assessing real property value in the local area. Decisions of the valuation authority cannot be contested with another administrative authority, but they may be taken before the courts.

Energinet.dk's Front Office administers the loss-of-value scheme and has placed forms and other material for use in the case-handling on its website, **www.energinet.dk**, where it also provides regular updates on new decisions.

6.A. A COMPREHENSIVE ACT ON RENEWABLE ENERGY

The Danish Promotion of Renewable Energy Act (L 1392 of 27 December 2008), which entered into force on 1 January 2009, covers, among other things, price supplements for installations producing electricity with renewable energy, technical and safety-related requirements for wind turbines, and special regulations for offshore wind turbines. The *Energy Policy Agreement of 21 February 2008* required that these regulations should be combined into one act on renewable energy.

Further to this agreement, the *Danish Promotion of Renewable Energy Act* also contains four new schemes aimed at promoting the local population's acceptance of and involvement in the development of onshore wind turbines: a loss-of-value scheme for neighbours of new wind turbines; an option-to-purchase scheme with preference given to the local population; a green scheme so that municipalities can improve the scenery and recreational values in areas where wind turbines are erected; and a guarantee scheme to support local initiative groups with preliminary investigations. All the schemes are administered by Energinet.dk.

6.B. THE LOSS-OF-VALUE SCHEME

Any party erecting new wind turbines with a height of 25 metres or more, including offshore wind turbines erected without a government tender procedure, must pay for any loss of value on real property if the erection of the wind turbines results in a loss of at least 1% of the property value. In order to give neighbours the opportunity to assess the consequences of the wind turbine project, the erector must draw up information material on the project and invite the neighbours to a public information meeting. The material must include a list of the properties lying within a distance of up to six times the wind turbine's total height. Energinet.dk, which must approve the information material, can require that the material should also include a visualisation of the project. The meeting must be convened with a reasonable period of notice by means of an announcement in local newspapers and must take place at the latest four weeks before the municipal planning process ends.

Property owners who believe, based on the information material and the information meeting, that the erection of the wind turbines will reduce the value of their property must notify the loss of value to Energinet.dk within four weeks of the meeting. If a property owner lives further away than six times the wind turbine's total height, the owner must pay a fee to Energinet.dk of DKK 4,000. Neighbours who live closer to the wind turbine project are not required to pay this fee. The fee is repaid if the property owner is granted the right to compensation for loss of value.

The wind turbine erector may enter into a voluntary agreement concerning compensation for loss of value with property owners who have notified their claims to Energinet.dk. If this is not done within four weeks, Energinet.dk will submit the owners' claims to a valuation authority. The Danish Minister for Climate and Energy has appointed five valuation authorities consisting of a lawyer and an expert in assessing real property value. The valuation authority will decide, on the basis of a specific assessment, the extent to which property owners' claims can be accommodated.

If the property owner's claim for compensation is upheld, the wind turbine erector will pay the valuation authority's costs. If the property owner's claim is rejected, Energinet.dk pays the case costs not covered by any fee of DKK 4,000. This cost is recouped from the electricity consumers as a PSO contribution.

Decisions of the valuation authority cannot be contested with another administrative body but may be brought before the courts as civil proceedings by the owner of the property against the wind turbine erector.

6.C. THE OPTION-TO-PURCHASE SCHEME

Erectors of wind turbines with a total height of at least 25 metres, including offshore wind turbines erected without a governmental tender, shall offer for sale at least 20% of the wind turbine project to the local population. Anyone over 18 years of age with his/her permanent residence according to the National Register of Persons at a distance of maximum 4.5 kilometres from the site of installation or in the municipality where the wind turbine is erected has the option to purchase. If there is local interest in purchasing more than 20%, people who live closer than 4.5 kilometres from the project have first priority on a share of ownership, but the distribution of shares should ensure the broadest possible ownership base.

In order to give local citizens an adequate decision-making platform, wind turbine erectors must provide information on the nature and financial conditions of the project. This must be done through sales material containing as a minimum the articles of association of the company that will be erecting the wind turbine, a detailed construction and operating budget, including the financing for the project, the liability per share, and the price of the shares on offer. The sales material must be quality-assured by a state-authorised public accountant. Energinet.dk must approve the sales material as a condition for the wind turbine erector obtaining the price supplement provided for in the *Danish Promotion of Renewable Energy Act*.

The wind turbine erector must run through the sales material at an information meeting convened with a reasonable period of notice by announcement in a local newspaper. Following the information meeting, local citizens have a period of four weeks to make a purchase offer. In the case of both the loss-of-value and option-to-purchase schemes, transitional regulations exempting wind turbines where the municipality has published a supplement to the municipal plan with an associated EIA or announced that the project does not require an EIA apply until 1 March 2009. The wind turbine project must also be connected to the grid before 1 September 2010.

6.D. THE GREEN SCHEME

In order to further promote the local council's commitment to wind turbine planning and local acceptance of new wind turbine projects, the *Danish Promotion of Renewable Energy Act* has introduced a green scheme for the financing of projects that enhance the scenery and recreational opportunities in the municipality. Energinet.dk, which administers the scheme, pays DKK 0.004 per kWh for the first 22,000 full-load hours from wind turbine projects that are connected to the grid on 21 February 2008 or later. The money for the green scheme is recouped from electricity consumers as a PSO contribution.

The money is lodged in a special account for the given municipality; the amount of money depends on how many wind turbines and of what size are connected to the grid in the municipality. A wind turbine of 2 MW generates a total sum of DKK 176,000. In order to

Photos: Visualisations by Birk Nielsen

Visualisations are an important element of an Environmental Impact Assessment (EIA) for new onshore wind turbine projects, and the method has been described in the report Store vindmøller i det åbne land – en vurdering af de landskabelige konsekvenser (Large wind turbines in the open countryside – an assessment of implications for the landscape). This example from the project in Gisselbæk illustrates the difference between a project with 3 x 1.75 MW wind turbines, each with a total height of 93 metres (top), and a layout of 3 x 3.6 MW wind turbines, each with a total height of 150 metres. The distance from the observer to the nearest wind turbine is 1.6 kilometres.

The visualisations were produced using a wind turbine model taken from the list in the WindPro software program: Siemens Wind Power's 3.6 MW wind turbine. The report's visualisation examples assume that the turbines have a standard grey anti-reflective coating. The spacing is three times the rotor diameter, which is recommended in respect of the wind turbine project's own aesthetics and to avoid problems with turbulence. For 3.6 MW wind turbines, this means a distance between the wind turbines of 321 metres.

Photo: Samsø Energy Academy

SAMSØ RENEWABLE ENERGY ISLAND: These three wind turbines, each 1 MW with a total height of 77 metres, are owned by local farmers and a wind turbine owners' association with around 450 members. The wind turbines, which were erected in 2000 as part of the Samsø Renewable Energy Island project, are an example of how it really is possible to create strong public support for the erection of large onshore wind turbines by financially involving the local population in new projects.

In addition to these three wind turbines near the village of Permelille, a further eight 1 MW wind turbines have been erected at two other sites on Samsø. The total construction cost for the 11 onshore wind turbines was around DKK 66 million, and in a normal year the turbines produce around 25,300 MWh, equivalent to the electricity consumption of some 6,500 households. Samsø Municipality has approximately 4,000 inhabitants.

promote local involvement in new wind turbine projects, during processing of the project the municipality may apply to Energinet.dk for a subsidy for certain development works or activities that draw on the full amount so that citizens become aware of the benefits that are obtained from the wind turbine erection.

However, the subsidy can only be paid once the wind turbine project is connected to the grid. If several wind turbine projects are implemented in a municipality, the subsidies can be used for one combined project. In order for the money to be paid, the municipality must demonstrate to Energinet.dk that the money will be used in accordance with the application.

The green scheme may wholly or partly finance development works for enhancing scenic or recreational values in the municipality. A subsidy may also be granted for municipal cultural activities and informational activities in local associations, etc., aimed at promoting acceptance of the use of renewable energy sources in the municipality. The municipalities may not raise complaints about Energinet.dk's handling of subsidies within the green scheme, but they can refer Energinet.dk's calculation of the municipality's share of the green scheme to the Energy Board of Appeal.

6.E. THE GUARANTEE SCHEME

In order to give local wind turbine owners' associations and other initiative groups the opportunity to initiate preliminary investigations, etc., for wind turbine projects, Energinet.dk has set up a guarantee fund of DKK 10 million that will make it easier for local initiatives to obtain commercial loans for financing preliminary investigations and keep the initiative-takers financially indemnified if the project cannot be realised. The money for the guarantee fund is recouped from electricity consumers as a PSO contribution.

A local initiative may apply to Energinet.dk for a guarantee to take out a loan of maximum DKK 500,000. There are conditions that the wind turbine owners' association or initiative group must have at least 10 members, the majority of whom have a permanent residence in the municipality, and that the project prepared involves onshore wind turbines with a total height of at least 25 metres or offshore wind turbines that are established without a government tender.

The guarantee can be given for activities that may be regarded as a natural and necessary part of a preliminary investigation into establishing one or more wind turbines. This might be an investigation of the siting of wind turbines, including technical and financial assessments of alternative sitings, technical assistance with applications to authorities, etc. However, it is a condition that at the time of application the project is financially viable in the opinion of Energinet.dk. Guarantees can be awarded for a maximum total sum of DKK 10 million. If this limit has been reached, new applications are placed on a waiting list. The guarantee shall lapse when the wind turbines are connected to the grid or if the local group sells its project to another party.

Energinet.dk's decisions concerning the guarantee fund may be contested with the Energy Board of Appeal.

6.F. ENERGINET.DK'S FRONT OFFICE

In order to ensure smooth, efficient administration of the four new schemes, Energinet.dk has set up a Front Office to take care of all direct contact with users of the schemes, while Energinet.dk's technical experts (back offices) undertake the actual legal and financial case-handling. In order to make the work easier for wind turbine erectors, neighbours and municipalities, there is a link (in Danish only) on the Energinet.dk website to a small library where all relevant application forms and other documents can be downloaded via the menu item "Nye vindmøller – hjælp til ejere, naboer og kommuner m.fl." (New wind turbines – help for owners, neighbours and municipalities, etc.).

The website also gives access to information (in Danish only) on the new schemes: the menu item "Kunder" (Customers) gives access to information and material on the loss-of-value scheme and the option-to-purchase scheme, while the menu item "Klima og miljø" (Climate and the environment) gives access to information on all four schemes via the submenu *"Danish Promotion of Renewable Energy Act"*. The Front Office staff can be contacted during business hours (9:00 am to 3:00 pm) by telephone on +45 70 20 13 53, or by e-mailing **fo@energinet.dk**.

The majority of initial inquiries have been about the loss-of-value scheme. In the first project to pass through the scheme's procedures, around half of the neighbours who made a claim for compensation obtained a voluntary settlement with the wind turbine erector, while the valuation authority has been involved in the other claims. Compensation was paid in two cases, while two claims were rejected. The valuation authority's specific decisions, which are published in anonymous form, can be monitored via the website **www.taksationsmyndigheden.dk** (in Danish only).

The website **www.energinet.dk** also contains a summary of the individual municipalities' accounts in the green scheme so that you can see whether a municipality currently has funds available for projects and activities.

Photos: Mogens Holmgaard/Vattenfall Wind Power

The Vattenfall electricity company, which is the largest owner of Danish onshore wind turbines, was also responsible for the largest project under the scrapping scheme at Nørrekær Enge, where 77 older wind turbines were replaced with 13 x 2.3 MW turbines. In the photo, the installers are setting up one of the new wind turbines, which were connected to the grid in 2009.

Factbox

The scrapping scheme

Part of the current projects involving new onshore wind turbines is being carried out under the scrapping scheme, which was agreed in the *Energy Policy Agreement of 2004*. Older and less efficient wind turbines with an output of maximum 450 kW can be dismantled in return for a scrapping certificate giving an erector the right to an extra supplement of DKK 0.08 per kWh for 12,000 full-load hours for new wind turbines with a total output up to twice as high as that of the dismantled turbines.

The scrapping scheme covers wind turbines totalling 175 MW, equivalent to the erection of new wind turbines with scrapping certificates for a total of 350 MW.

The scheme for earning scrapping certificates and redeeming them for new projects is administered by Energinet.dk, which also pays the price supplements connected with the scrapping scheme as a PSO-financed contribution.

7. TARIFFS FOR ELECTRICITY PRODUCED BY WIND TURBINES

Factbox

Tariffs for electricity produced by wind turbines

The development of wind power in Denmark has been promoted since the late 1970s by paying wind turbine owners a supplement to the electricity production price. Even though the electricity market in Denmark was liberalised in 1999 so that the market price could fluctuate according to supply and demand, the wind turbine owners were guaranteed a fixed feed-in tariff.

In the *Energy Policy Agreement of 2004* the wind turbine owners' production subsidy was established as a supplement to the market price of DKK 0.10 for 20 years. In the Energy Policy Agreement of February 2008 it was decided to increase the production subsidy to make it more attractive to erect onshore wind turbines.

As the 4,700 or so onshore wind turbines were erected at different times, the production subsidy varies depending on the date of grid connection and the size of the wind turbines. The detailed conditions are set out in the *Danish Promotion of Renewable Energy Act*, which contains all the tariffs for electricity produced by wind turbines.

New onshore wind turbines connected to the grid after the *Energy Policy Agreement of 21 February 2008* receive a supplement to the market price of DKK 0.25 per kWh. This supplement applies for the first 22,000 full-load hours, after which the wind turbine owner only receives the market price. Furthermore, a supplement of DKK 0.023 per kWh is paid to cover balancing costs for the full lifetime of the wind turbine.

New wind turbines established with a scrapping certificate receive an extra supplement of DKK 0.08 per kWh for 12,000 full-load hours.

Offshore wind turbines established under an open-door procedure receive the same supplement as new onshore wind turbines, i.e. DKK 0.25 per kWh plus DKK 0.023 per kWh. In the case of offshore wind turbines established as part of a government tender, the supplement depends on the price at which the tendering party is prepared to produce electricity. This price will usually depend on the estimated construction costs, the local wind conditions, and the project developer's financing terms.

7.A. THE NEED FOR FINANCIAL SUPPORT FOR WIND TURBINE ELECTRICITY

Right from the late 1970s, there has been financial support for electricity produced by wind turbines. In the early years, this support took the form of both installation grants and electricity production subsidies. Since the beginning of the 1990s, the support has taken the form of a guaranteed feed-in tariff or a supplement to the market price. The support is offered as compensation for wind turbine owners because electricity production from wind turbines still cannot compete financially with conventional production at power plants using coal, natural gas or oil.

The current supplement to the market price is paid by Energinet.dk, which recoups the sum as a public service obligation (PSO). The amount is indicated on electricity bills. In recent years, when the average market price in the Nordic spot market has been fluctuating between DKK 0.20 and 0.35 per kWh, the PSO tariff has been around DKK 0.10 per kWh. As well as wind turbines, which receive around half of these PSO contributions for environmentally friendly electricity production, the contributions are also spent on supporting decentralised CHP plants, electricity production from biomass, solar power, etc.

7.B. PRICE SUPPLEMENTS FOR ONSHORE WIND TURBINES

The price supplement for electricity produced by wind turbines is regulated in the *Danish Promotion of Renewable Energy Act* in accordance with the *Energy Policy Agreement of 21 February 2008*. Here, a broad political majority in the Danish Parliament agreed to increase the supplement to make it more attractive to erect onshore wind turbines. The electricity produced is supplied to the electricity supply grid, and the turbine owner sells the actual electricity on the market under market conditions. A DKK 0.25 supplement to the market price is paid for electricity produced by wind turbines connected to the grid on or after 21 February 2008. The price supplement applies for the first 22,000 full-load hours. Furthermore, a supplement of DKK 0.023 per kWh is paid to cover balancing costs throughout the turbine's lifetime.

In the case of wind turbines that were connected to the grid before 21 February 2008, there are special regulations that depend on the date of connection and the size.

Household wind turbines and small turbines, i.e. wind turbines with an output of less than 25 kW, that are connected in a household's own consumption installation, receive a price supplement which, together with the current market price, amounts to DKK 0.60 per kWh.

If a wind turbine erector has earned or purchased scrapping certificates from older wind turbines with an output of 450 kW or less and dismantles the turbines in the period 15 December 2004 to 15 December 2010, the erector may receive a scrapping price supplement of DKK 0.08 per kWh, which is added to the general price supplement of DKK 0.25 per kWh. The scrapping price supplement is paid for the first 12,000 full-load hours at double the dismantled wind turbine's output. The supplement is conditional on the wind turbine being connected to the grid by 31 December 2010.

7.C. PRICE SUPPLEMENTS FOR OFFSHORE WIND TURBINES

The price supplement for electricity produced by offshore wind farms established as part of a government tender is determined as part of the given tender. The winners of the tenders to date have been the bidders that could offer the lowest feed-in tariff. In the two government tenders carried out so far, the feed-in tariff for Horns Rev II, which is owned by DONG Energy, was set at DKK 0.518 per kWh for 10 TWh, corresponding to around 50,000 full-load hours, and the feed-in tariff for Rødsand II, which is owned by E.ON AB, was set at DKK 0.629 per kWh for 10 TWh, corresponding to around 50,000 full-load hours. Wind turbines established under an open-door procedure receive the same price supplement as new onshore wind turbines, i.e. DKK 0.25 per kWh for 22,000 full-load hours plus DKK 0.023 per kWh for the full lifetime of the turbine.

8. INCORPORATION OF WIND POWER INTO THE ELECTRICITY SYSTEM

8.A. VARYING ELECTRICITY PRODUCTION OF WIND TURBINES

Over the decades Denmark has built up a well-functioning electricity system that gives consumers technical supply reliability that is among the best in the world. The electricity system has traditionally been based on a limited number of large thermal power stations whose heat surplus is used to feed the district heating supply of the largest towns. In the last 15-20 years this set-up has changed significantly, with the predominant proportion of new capacity being established as decentralised CHP plants, waste-based CHP plants, and wind turbines. This decentralised electricity production set-up has required the development of new methods for controlling and regulating the electricity system.

With a total installed capacity of around 3,200 MW, wind turbines today can annually cover around 20% of domestic electricity supply. By way of example, to cover around half of the electricity consumption with wind power in 2025 would require an increase to around 6,700 MW.

With the current wind turbine capacity there are already periods of the year when the electricity production of the wind turbines exceeds the total Danish consumption. This occurs in particular at night, when the wind blows strongly.

In a European context, Denmark is located between Norwegian and Swedish systems dominated by hydroelectric power and a continental system dominated by thermal power stations south of the border. In Germany, the Netherlands and Belgium, as well as in Norway and Sweden, there are currently plans for a major development of wind power, and the Danish electricity system will therefore assume an important role in linking areas with hydroelectric power, wind power and thermal electricity production respectively. The cross-border connections from Denmark to Norway, Sweden and Germany currently play a key role in optimum utilisation of the fluctuating electricity production of the wind turbines. When it is windy in Denmark and electricity consumption is relatively low, Denmark exports electricity to Norway and Sweden, which turn down their hydroelectric power stations' turbines accordingly. In this way the hydroelectric power stations' water reservoirs function as an indirect store for wind-power-produced electricity because the hydroelectric power stations can quickly increase their production when the wind turbines can no longer cover such a large proportion of electricity consumption.

As the electricity system also has to be able to supply Danish consumers in periods when Danish wind turbines are not producing due to a lack of wind or storms, the system can either be fed by thermal power stations or via cross-border connections. In this way, the development of strong cross-border connections acts as an alternative to Danish back-up capacity with thermal power stations.

An anticipated major development of Danish wind power capacity increases the need to develop methods and means to make electricity consumption more flexible so that electricity consumers are encouraged to reduce consumption in periods of low production capacity in return for increasing consumption when production is high. Practical trials have demonstrated various forms of flexible electricity consumption: electric heat consumers can be switched off for a few hours without inconvenience; cold stores can switch off the electricity supply without the temperature increasing to a critical level; washing machines and dishwashers in private homes can be switched on when electricity prices are low; and so on.

However, a greater effect on the electricity system's overall flexibility can be achieved by integrating electric car batteries and heat pumps into a flexible electricity consumption. This will help reduce Denmark's greenhouse gas emissions from the sectors of society that are not covered by the European CO_2 quota regulation. (The European quota regulation regulates CO_2 emissions for large dischargers such as electricity and heating plants and energy-intensive industry.) Given that from 2013 Denmark will have a special climate emission

Photos: Ricky John Molloy/Energinet.dk

GREAT BELT ELECTRICITY LINK: In order to be able to connect up the two separate parts of Denmark into one electricity system, work has been carried out in recent years on an electricity link under the Great Belt. The link is expected to begin operating in 2010 with a transmission capacity of 600 MW, equivalent to about one tenth of the total Danish electricity consumption on a cold winter's day.

The Great Belt link has a construction budget of approximately DKK 1.2 billion and estimated annual operating costs of just over DKK 100 million. This is regarded as a good investment for Danish society because the link will make it possible to exploit Danish wind turbine power more efficiently within Denmark.

The link will also reduce the need for reserve production capacity in the electricity system and increase competition in the electricity market.

The electricity link consists of a 32 km underwater cable and two land cables of 16 km on Funen and 10 km on Zealand. The link will run from Fraude on Funen to Herslev on Zealand.

The above photos show the underwater cable being laid in summer 2009.

target duty for the sectors that are not covered by the quota system, the reduction of emissions in these sectors will be of particular value. At the same time, the transport sector is still completely dominated by oil, from which Denmark has a long-term goal to free itself. There are therefore environmental, supply-related and economic benefits associated with converting energy consumption from the sectors that are not quota-regulated into electricity and district heating. At the same time, an increase in electricity consumption's share of total Danish energy consumption makes it possible to use a relatively larger proportion of the electricity production from the wind turbines in Denmark, especially if this can be done with a more flexible electricity consumption.

8.B. RESEARCH INTO AN INTELLIGENT ENERGY SYSTEM

Converting the Danish energy system requires the introduction of more intelligent and self-regulating methods for controlling the system. In order to maintain a high technical level of supply reliability there must be a constant balance between production/supply and consumption in the Danish electricity system. As the electricity production from wind turbines can be changed at very short notice, there is a need for advanced communication between production installations, the system operator and consumers. The quicker and more efficiently the system operator can regulate both production and consumption, the lower the energy system's economic costs become.
In order to ensure this development of the electricity system, for several years intensive research has been carried out into advanced methods for regulating the electricity system, and Danish research environments are among the most competent in the world. Furthermore, research is being undertaken into components that make individual wind turbines easier to regulate by the system operator. By combining new advanced regulation methods with intelligent electric meters installed in the premises of consumers, the operation of the electricity system can be optimised and it will be technically possible to incorporate ever greater amounts of fluctuating electricity production from wind turbines, wave power installations, solar cells, etc. ●

Illustration: Energinet.dk

Key

- 400 kV overhead line, a/c
- 400 kV cable, a/c
- Overhead line, d/c
- Cable, d/c
- Transformer station
- Converter station

The map of Denmark from Energinet.dk shows the Danish high-voltage grid and associated cross-border connections to Norway, Sweden and Germany. Strong cross-border connections are regarded as a vital precondition for efficient utilisation of the varying Danish electricity production from wind turbines.

Currently there are plans to expand the connections between Denmark and Norway (Skagerak IV) and between Denmark and Germany. Furthermore, it is possible to expand the connections between Denmark, Sweden and Germany by connecting a large offshore wind farm on Kriegers Flak to the grid. A possible offshore wind farm south of Læsø could also pave the way for a stronger connection between Jutland and Sweden. And finally, work is being carried out on plans for an underwater cable connection between Denmark and the Netherlands (Cobra), which in the long term would make it possible to carry electricity production from Denmark and Danish offshore wind farms in the North Sea to continental Europe.

FURTHER INFORMATION

The legal provisions on wind power can be found in the *Danish Promotion of Renewable Energy Act* (L 1392, adopted by the Danish Parliament on 27 December 2008), bill no. 55 of 5 November 2008 with explanatory notes. Both can be downloaded (in Danish) from **www.retsinformation.dk**.

More detailed regulations on onshore wind turbines can be found in *Circular no. 9295 of 22 May 2009* on planning and rural zone permits for the erection of wind turbines. The Circular and the associated guideline (no. 9296) can be downloaded (in Danish) from **www.blst.dk/Landsplan/Vindmoeller**.

The Birk Nielsen visualisation report entitled *Store vindmøller i det åbne land – en vurdering af de landskabelige konsekvenser (Large wind turbines in the open countryside – an assessment of implications for the landscape)* can be downloaded (in Danish) from **www.skovognatur/Udgivelser/2007/Storevindmoller.htm**.

The report of the Danish Government's Planning Committee for Onshore Wind Turbines, published in 2007, can be downloaded in Danish from **www.blst.dk/Landsplan/Vindmoeller/Vindmoelleudvalg**. An interactive map for assistance with wind turbine planning can be accessed via **www.blst.dk/Landsplan/Vindmoeller/afstandskort**.

An English summary of the report of the Danish Government's Committee for Future Offshore Wind Power Sites entitled *Future Offshore Wind Power Sites – 2025*, published in April 2007, can be downloaded from **www.ens.dk/en-US/supply/Renewable-energy/WindPower/offshore-Wind-Power/Future-offshore-wind-parks/Sider/Forside.aspx** and the updated *Offshore Wind Turbine Action Plan 2008*, published in April 2008, can be downloaded (in Danish) from **www.ens.dk/da-DK/UndergrundOgForsyning/VedvarendeEnergi/Vindkraft/Sider/Forside.aspx**.

The Danish Ministry of the Environment's Wind Turbine Secretariat has a website at **www.vind.mim.dk** and can be contacted during business hours (09:00 am to 4:00 pm) by telephone on +45 72 54 05 00, or by e-mailing **vind@mim.dk.**

Energinet.dk's Front Office can be contacted during business hours (09:00 am to 3:00 pm) by telephone on +45 70 20 13 53, or by e-mailing **fo@energinet.dk.**

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Amaliegade 44, 1256 Copenhagen K
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Danish Energy Agency
Amaliegade 44
DK-1256 Copenhagen K
Tel: +45 33 92 67 00
Fax: +45 33 11 47 43
ens@ens.dk
www.ens.dk

Health effects related to wind turbine sound

Frits van den Berg

Public Health Service Amsterdam

Amsterdam, the Netherlands

Irene van Kamp

National Institute for Public Health and the Environment

Bilthoven, the Netherlands

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.

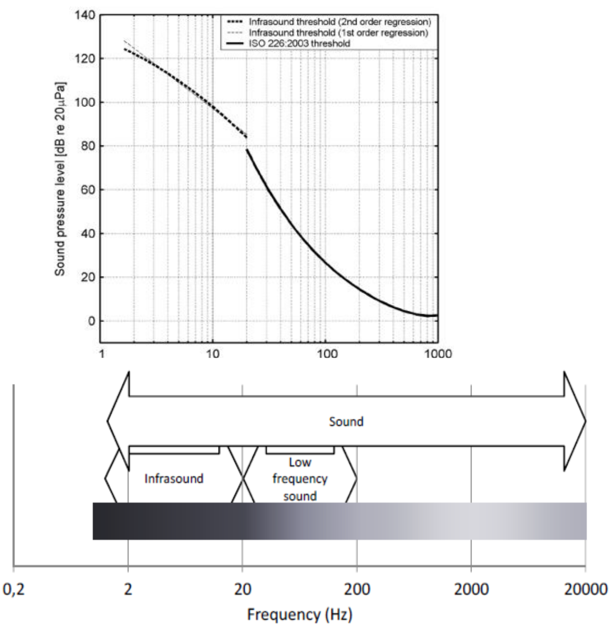
Wind turbine sound can sometimes be tonal, i.e. one can hear a specific pitch. This can be mechanical sound from the gear box and other devices in the turbine and this was a relevant source for early turbines. However, this has been reduced and is generally not an important source for modern turbines. 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.

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

[*] 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.

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.

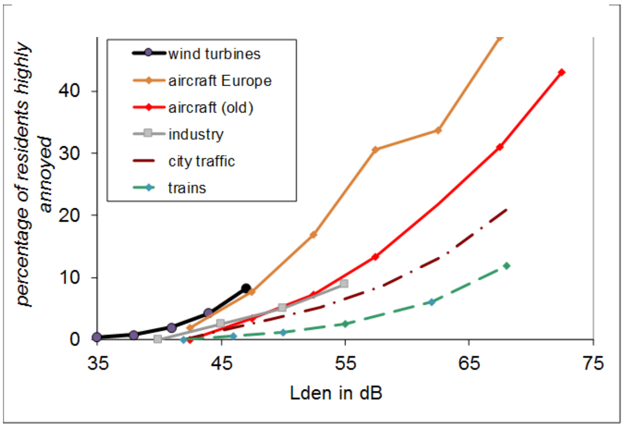
The next sections will describe the state of the art in more detail per health effect. Note that the description is limited to the effects of wind turbine sound in general in the "normal" frequency range. Findings from studies, addressing specific impacts of the low frequency component and infrasound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

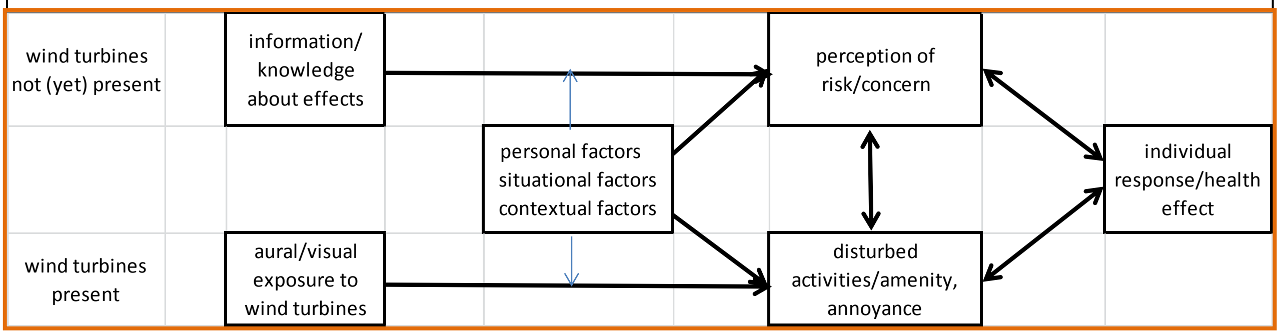
Attitude and media coverage are just a few elements of the complex process which plays a role in decision making for siting wind turbines. Most recent studies conclude that social acceptance of wind projects is highly dependent on a fair planning process and local involvement.

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)

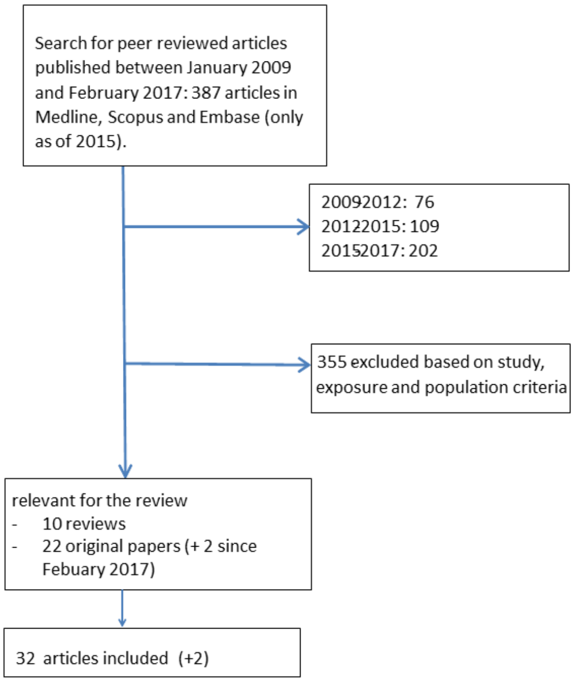
24 limit 23 to ed=20150122-20161228 (81)

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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A new wind farm noise standard for New Zealand NZS 6808:2010

Dr Stephen Chiles

URS, Christchurch, New Zealand

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ABSTRACT

New Zealand Standard NZS 6808 provides methods for the prediction, measurement, and assessment of sound from wind turbines. The 1998 version was written prior to significant wind farm development in New Zealand, and while the basic methodology proved robust, experience and research over the following decade brought to light numerous refinements and enhancements which are now addressed in the new 2010 version. This paper describes the revision process, and explores the technical issues addressed and key areas of debate. This was a challenging project, with wide ranging views both within the committee and from hundreds of public submissions.

INTRODUCTION

Currently there are eleven wind farms operating in New Zealand with a total capacity of just under 500 MW. These provide up to 5% of the country's electricity. There are active proposals for numerous further wind farms, which collectively will have many times this capacity.

Several recent wind farm developments and proposals have been highly contentious, with local objections attracting significant media coverage. Using the old version of NZS 6808 [1], the consent conditions associated with these projects ballooned, as regulators and residents sought tighter controls and increasingly more prescriptive measurement and assessment procedures. This led to substantial inefficiencies and inconsistencies. These matters are now dealt with in the revised version of NZS 6808 [2], which once again provides a standardised approach for managing wind farm sound in New Zealand.

The original 1998 version of NZS 6808 was based on the United Kingdom 1996 ETSU report [3]. There were minor adjustments made, which included replacing the L_{90} descriptor with the L_{95}, as that was used to describe background sound in New Zealand at the time. Also, rather than the different daytime and night-time ETSU noise limits, the fixed part of the noise limit was set at 40 dB at all times in NZS 6808. The 'background +5 dB' variable part of the noise limit from the ETSU report was retained in NZS 6808.

Since its publication, NZS 6808:1998 was used for all wind farms in New Zealand. In the absence of an Australian Standard prior to 2010, NZS 6808 was also adopted in the state of Victoria.

The main thrust of the 2010 revision of NZS 6808 related to technical refinements and incremental enhancements. However, probably the most controversial addition to the Standard is the provision for a more stringent 'high amenity noise limit' where justified by special local circumstances.

PROCESS

NZS 6808 was first published in 1998. In accordance with Standards New Zealand's procedures, it was formally reviewed in 2004. At that time various potential technical refinements were identified, but the Standard was still being successfully implemented. In practice, most acousticians were applying the key changes now included in the 2010 revision. The decision was made in 2004 not to revise NZS 6808 yet.

By 2007 the Standard was coming under increased pressure, with questions being raised over how it should be applied. This led the New Zealand Wind Energy Association and the Energy Efficiency and Conservation Authority to commission research into the technical issues in question [4]. The results of this research then triggered another formal review of NZS 6808 by Standards New Zealand.

The review started with a scoping workshop in late 2007, where all stakeholders agreed that a full revision of the Standard was appropriate. Standards New Zealand then constituted a technical committee in mid 2008 to conduct the revision. The majority of the committee's work was conducted in the second half of 2008. The author chaired this technical committee.

Standards New Zealand forms technical committees by inviting organisations that represent relevant stakeholders to nominate a technical expert. In this instance, the nominating organisations were:

- Energy Efficiency and Conservation Authority
- Executive of Community Boards
- Local Government New Zealand
- Massey University
- Ministry for the Environment
- Ministry of Health
- New Zealand Acoustical Society
- New Zealand Institute of Environmental Health Inc.

- New Zealand Wind Energy Association
- Resource Management Law Association
- University of Auckland

The only representative without particular technical expertise was the representative of the Executive of Community Boards. A resident adjacent to a large wind farm was nominated. That individual had good technical aptitude, and made a valuable contribution, providing critical review and questioning all assumptions.

Given the strong public interest in the revision, the evidence based approach used to make decisions needed to be documented to a greater degree than normal. The committee initially split into working groups addressing different issues such as noise limits, measurements and predictions. Each working group submitted recommendations back to the main committee, where they were vigorously debated and tested against the evidence. The process was focussed on achieving consensus, which requires general agreement, but not unanimity.

A draft of the proposed revision was circulated for public comment in early 2009. The draft elicited over 600 public submissions, which is unusual for a technical standard, and reflects the public criticism of sound from some wind farms in New Zealand. The committee made decisions on each individual submission and prepared a final draft in mid 2009.

The last action for a technical committee is a 'postal ballot'. In this instance, several unexpected issues emerged at the ballot through a number of negative votes. The draft was therefore amended over the following months until consensus was reached at the second postal ballot later in 2009.

There was still one negative vote at the second postal ballot, from the representative of Massey University. That individual has publicised his views [5], and acknowledges they are contrary to most international scientific opinion. The remainder of the committee could not reconcile the arguments he advanced against the Standard, with scientific evidence, or the framework for all other noise assessments in New Zealand.

Due to the negative vote and public sensitivity around this Standard, the Standards Council would not issue its final approval to publish the revision of NZS 6808 until it was demonstrated in detail that Standards New Zealand had followed correct procedures, and there were legitimate technical reasons not to accept the issues raised by the negative vote. This process and editorial matters resulted in publication of the new Standard on 1 March 2010, 'NZS 6808:2010'.

NOISE LIMITS

The committee found that the previous wind farm noise limit of 40 dB L_{A95} or background +5 dB is still appropriate, as it provides protection from adverse health effects and maintains reasonable residential amenity.

In terms of potential adverse health effects, the committee was guided primarily by the internal noise criteria of 30 dB L_{Aeq} given by the World Health Organisation [6]. New Zealand experience is that a limit of 40 dB L_{A90} outside a dwelling will result in compliance with this internal limit, with windows slightly ajar for ventilation. The background + 5 dB variable part of the noise limit was retained, as the potential effect of wind turbine sound reduces as the background sound increases, and a constant limit of 40 dB L_{A90} would be meaningless at higher wind speeds as there would be no reliable way of measuring compliance.

For general environmental noise, NZS 6802 [7] provides a guideline night-time noise limit at dwellings of 45 dB $L_{Aeq(15\ min)}$. The way the New Zealand planning framework operates is that this guidance can be modified as it is implemented in each local planning document ('district plan') throughout the country. However, most plans set night-time limits of 40 or 45 dB $L_{Aeq(15\ min)}$, or L_{A10} in older plans. Therefore, the wind farm noise limit is consistent with noise limits for, say, industrial or agricultural activities in rural areas.

The committee also made reference to wind farm noise limits in other countries, and found that while there is some variation, the noise limits in NZS 6808 are comparable with the majority of countries.

Several issues arose in public submissions regarding noise limits. Many of these submissions, such as requests for a buffer zone around wind farms of several kilometres, regardless of the wind farm scale or local conditions, were simply not compatible with the effects-based approach taken by the New Zealand planning system. The benefit of the method in NZS 6808 is that it accounts for the actual wind farm layout, turbine type, wind conditions, topography and background sound, thus providing an effects-based assessment.

It appears that some of the public submissions were seeking inaudibility as a de facto criterion for wind farms, but this is not a criterion applied to any other sound source in New Zealand. Another theme from submissions was a desire to allow for people either sleeping outdoors on their decks or sleeping with full height doors/windows left wide open. Night-time noise limits for all other sound sources in New Zealand are set on the basis of people inside with windows only partially open for ventilation. The committee did not find any reason for treating wind farms differently to other sound sources in rural areas.

Special audible characteristics

An area of significant improvement in the 2010 revision is the treatment of 'special audible characteristics'. These are distinguishing features of wind farm sound that attract a 5 dB penalty if present. In 1998 this was addressed in only a basic manner.

The first enhancement is NZS 6808 now states that, if it is known in advance that a special audible characteristic will be present at a dwelling, the wind farm should not proceed. The penalties are now only to cater for unexpected characteristics that arise during or after commissioning.

Since 1998 a sophisticated test method for tonality has been developed and is included in ISO 1996-2 [8]. NZS 6808 now simply refers to that Standard. There is an option for a subjective assessment or a simplified assessment, but an objective assessment using ISO 1996-2 will take precedence.

Another issue that has emerged internationally since 1998 is the possibility of 'aerodynamic modulation' [9] of wind farm sound. However, it has been observed at very few wind farms and none in New Zealand. An interim test method has now been provided in NZS 6808 should aerodynamic modulation be suspected. Aerodynamic modulation as a special audible characteristic will be deemed to exist if the measured A-weighted peak-to-trough levels exceed 5 dB on a regularly varying basis, or if the measured third-octave band peak-to-trough levels exceed 6 dB on a regular basis in respect of the blade pass frequency. It is acknowledged that a more refined test may be developed in future.

High amenity noise limit

Generally, when there are low background sound levels at dwellings, wind farms are not operating. However, there can be dwellings in sheltered valleys which are quiet at times when there is still enough wind for a wind farm to be operating. This concern was raised for a particular project in New Zealand, where the local planning document also set a lower than normal noise limit for general environmental noise. In that case the fixed part of the wind farm noise limit was reduced to 35 dB L_{A95} when those wind conditions occur. To detect those wind conditions an extensive and elaborate semi-permanent sound and wind monitoring system was installed at a number of dwellings around the wind farm. When background sound levels at a dwelling are lower than 25 dB L_{A95} and the wind speed at 10 m above ground level is less than 1.5 m/s, the lower noise limit applies. These controls are highly inefficient and relatively expensive to implement. In this case, the complexity of the noise limits appears to have created additional anxiety for the residents.

With this precedent of a lower wind farm noise limit, similar controls have since been proposed for several other wind farms. However, given the justification for the 40 dB L_{A90} noise limit described above and the consistency with noise limits for other sound sources, it is not obvious why this lower limit should be more widespread.

The committee recognised that there may be some areas in New Zealand where acoustics amenity is valued to a greater degree than any development. For example, there are a handful of areas in the country where the general environmental noise limit is less than 40 dB. The project for which a reduced wind farm noise limit was first imposed was in one of those areas. The committee decided that in these cases, where a public process had resulted in a local planning document providing for increased protection of amenity, it may be appropriate to provide for a 'high amenity noise limit' of 35 dB L_{A90} or background +5 dB, in the evening and at night. Figure 1 illustrates the wind farm noise limits in NZS 6808.

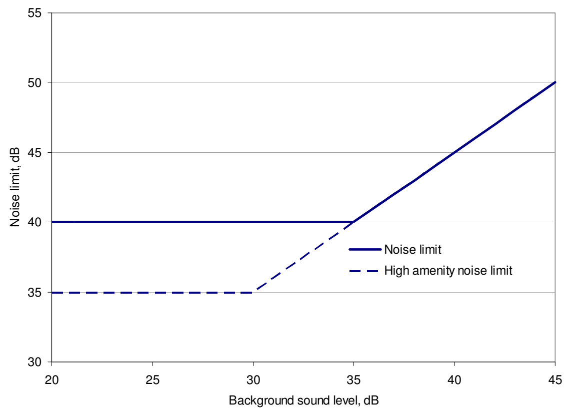

Figure 1. NZS 6808 noise limits

The committee sought to reduce the complexity of the control systems previously used to identify sensitive times when a high amenity noise limit should apply. It was found that there are no simple relationships that will identify all sensitive times. Even with the elaborate monitoring systems at dwellings used previously, a proportion of those times are missed. However, it was decided that this was acceptable as 40 dB L_{A90} still protects health and maintains reasonable amenity. A new control was devised that captures a similar or greater number of sensitive times, simply by using the wind farm wind speed. In cases where the high amenity noise limit is justified, it now applies when the wind farm wind speed is 6 m/s or less. This provides a more efficient control that should provide greater benefit for communities.

Alleged health effects

Another key issue that exercised the committee was reported adverse health effects from wind turbine sound, such as 'vibroacoustic disease', 'wind turbine syndrome', and various other low frequency sound and vibration effects. The committee reviewed a substantial volume of international literature on these alleged effects, including papers published through to the middle of 2009 at the International Meeting on Wind Turbine Noise.

Despite the volume of material on some of these alleged health effects, the committee unanimously found that in all cases the evidence did not show any causal link between the effects claimed and wind turbine sound. There were fundamental weaknesses in the scientific methodology in all cases. No evidence was found that a precautionary approach with lower noise limits for wind turbine sound is necessary.

Some recent wind farm proposals in New Zealand have created significant anxiety in the surrounding community. This has been fuelled by the convictions of those promoting these alleged health effects, and it remains a challenge to communicate the wider scientific view, such that communities may then experience less anxiety.

TERMINOLOGY

A number of changes have been made to the terminology used in NZS 6808. The most notable are:

$L_{A90(10\ min)}$ – NZS 6808 previously used the L_{95} descriptor for background and wind farm sound levels. However, in all other New Zealand Standards since 1999, the L_{90} has been adopted for background sound. This has now been changed in NZS 6808, and it has also been brought in line with international standards by adding the frequency-weighting and measurement time interval (e.g. $L_{A90(10\ min)}$). Comparisons were made between L_{90} and L_{95} data for wind farms and it was shown that there were less than 0.5 dB differences. Therefore no amendment was made to the noise limits.

Wind turbine – The 1998 version of NZS 6808 used the acronym 'WTG' for wind turbine generator. However, this is no longer used in international standards, and the 2010 version of NZS 6808 just uses the words 'wind turbine'.

Small wind turbine – Under the 1998 version of NZS 6808 there was no differentiation of wind turbine sizes, and it was possible for an extensive measurement methodology to be required even for small wind turbines. The 2010 revision now includes a definition of small wind turbine, taken from IEC 61400-2 [10], as anything with a swept area less than 200m^2. This encompasses reasonable sized wind turbines with up to 8 m blade lengths, but currently in New Zealand turbines tend to be clearly one side or the other of this point. For small wind turbines the Standard now allows for compliance with the general environmental noise limits and also provides for on/off testing.

MEASUREMENTS

NZS 6808 is based on wind turbine sound data measured in accordance with IEC 61400-11 [11]. This currently requires wind data to be referenced to 10 m above ground level. It has been shown [12] that the simplistic algorithm to account for wind shear in IEC 61400-11 can introduce significant errors, particularly with taller wind turbines. This issue has been eliminated in the 2010 revision of NZS 6808 by referencing all wind speed data to the wind turbine hub-height. Improved techniques for measuring and modelling wind speed mean that wind farm developers are usually able to provide hub-height wind speeds to a good degree of accuracy.

The background +5 dB variable part of the noise limit requires a relationship to be determined between background sound levels and wind farm wind speed. In some cases good correlations of the data are not achieved, such as when sound levels are dominated by road-traffic, or when a location is sheltered by terrain in certain wind directions. The committee determined that a prescriptive procedure for the correlations would not be practical as there are too many site specific factors. However, significant additional guidance has been provided, with various factors now required to be taken into account. It is now explicit the degree to which data may need to be separated into different times or wind conditions. Also, notes are provided for issues such as measurements near water courses and trees.

Uncertainty

Historically, uncertainty associated with environmental sound measurements in New Zealand has not been reported. In common with other New Zealand acoustics Standards that have been recently revised, NZS 6808 now makes reference to the University of Salford guidelines on uncertainty [13], and promotes this as good practice. At this stage, given that the acoustics industry needs to develop in this area, it is not mandatory to state the uncertainty of measured levels.

PREDICTIONS

The 1998 version of NZS 6808 provided a simple propagation algorithm accounting just for distance attenuation and air absorption, based on 500 Hz. While this is generally conservative, the use of air absorption at 500 Hz can introduce significant errors. Most practitioners using acoustics software were implementing more sophisticated propagation models.

NZS 6808 now specifies a wide range of factors that must be taken into account in propagation modelling and references ISO 9613-2 [14] as an appropriate method. A simplified method is still provided in an appendix, but the limitations are clearly set-out and octave-bands are required for air absorption.

An issue that arises with the NZS 6808 method is that wind turbine sound power data in accordance with IEC 61400-11 is in terms of L_{Aeq}, whereas the noise limits are in terms of L_{A90}. It has previously been suggested that an adjustment to predications is justified as the L_{A90} will be lower than the L_{Aeq}. However, the committee decided that as the difference is variable [4], it is better to assume that a prediction based on L_{Aeq} source data is taken to be an L_{A90}. This provides a small degree of conservatism in the predictions.

RESOURCE MANAGEMENT ACT

In New Zealand, the planning and consenting process is controlled by the Resource Management Act. Under this Act, a couple of issues often arise which were not adequately addressed in the 1998 version of NZS 6808.

Reverse sensitivity

'Reverse sensitivity' issues could arise if a new dwelling was constructed adjacent to an existing wind farm, and then complaints by the new residents restricted the operation of the wind farm. This can be addressed by alerting prospective residents to the effects of a consented or existing wind farm, and NZS 6808 now provides guidance on this issue.

Cumulative effects

NZS 6808 was previously silent on the issue of cumulative noise effects from multiple wind farms or a single wind farm developed in stages. It has now been made clear that the noise limits apply to the combination of all wind farm sound affecting any dwelling, and that background sound level measurements used for determining the background +5 dB limits must exclude any existing wind farm sound.

Conditions

In New Zealand, development or planning ('resource') consents are usually granted subject to conditions. These conditions may reference Standards, but they also have to explicitly include the actual noise limits and assessment points.

As noted previously, in the author's opinion, convoluted consent conditions for recent wind farms have resulted in significant inconsistency and have contributed to community confusion and anxiety. To ensure the new revision of NZS 6808 is applied consistently and robustly, a set of model conditions have been provided in an appendix.

CONCLUSIONS

A two year revision process was undertaken for the New Zealand wind farm noise Standard, NZS 6808, from 2008 to publication in 2010. The fundamental method of the 1998 version was found to be robust. The key changes made were a raft of technical refinements and incremental enhancements. Other changes include provision for a high amenity noise limit in specific areas.

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Noise annoyance from wind turbines - a review

Eja Pedersen, Högskolan i Halmstad

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Noise annoyance from wind turbines
a review

Eja Pedersen, Högskolan i Halmstad

NATURVÅRDSVERKET
SWEDISH ENVIRONMENTAL PROTECTION AGENCY

Orders

Order telephone: +46 (0)8-505 933 40
Order telefax: + 46 (0)8-505 933 99
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SE-161 11 Bromma, Sweden
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Naturvårdsverket, Swedish Environmental Protection Agency
Telephone: +46 (0)8-698 10 00 (switchboard)
www: naturvardsverket.se
Address: Naturvårdsverket, SE-106 10 00 Stockholm, Sweden

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Preface

Wind power is a relatively new generator of electricity in Sweden. Legislation and regulation regarding noise from wind turbines in Sweden have been discussed. Eja Pedersen at Halmstad University has at the request of the Swedish Environmental Protection Agency prepared this report as a base for further discussions on regulation and guidelines on noise from wind turbines in Sweden. The report reviews the present knowledge on perception and annoyance of noise from wind turbines in residential areas as well as in recreational areas. It also summarizes regulations in some European countries. The author Eja Pedersen is responsible for the content of the report.

Stockholm, August 2003

Contents

Summary

This study summarises present knowledge on noise perception and annoyances from wind turbines in areas were people live or spend recreation time. There are two main types of noise from a wind turbine: mechanical noise and aerodynamic noise. The aerodynamic noise emits from the rotor blades passing the air. It has a swishing character with a modulation that makes it noticeable from the background noise. This part of the wind turbine noise was found to be the most annoying.

Field studies performed among people living in the vicinity of wind turbines showed that there was a correlation between sound pressure level and noise annoyance, but annoyance was also influenced by visual factors such as the attitude to wind turbines' impact on the landscape. Noise annoyance was found at lower sound pressure levels than in studies of annoyance from traffic noise. There is no scientific evidence that noise at levels created by wind turbines could cause health problems other than annoyance.

No studies on noise from wind turbines in wilderness areas have been found, but the reaction to other noise sources such as aircraft have been studied. In recreational areas, the expectation of quietness is high among visitors, but wind turbines are, in contrary to aircraft, stationary and could be avoided by recreationists. The visual impact of wind turbines might though be the dominant source of annoyance.

Regulations on noise from wind turbines are based on different principles. Some states, e.g. Denmark, have a special legislation concerning wind turbines, while others, like Sweden, have used recommendations originally developed for a different noise source. The noise level could either be absolute, as in Germany, or related to the background noise level as in France. This background noise level could be standardised, measured or related to wind speed.

Sammanfattning

Denna rapport har tagits fram av Eja Pedersen, Högskolan i Halmstad på uppdrag av Naturvårdsverket. Syftet är att ge underlag för fortsatta diskussioner om bedömning av ljud från vindkraftverk i Sverige

Rapporten sammanfattar kunskapsläget kring människors uppfattning och störning av buller från vindkraftverk vid bostäder och i friluftsområden. Vindkraftverk ger upphov till två typer av ljud: mekaniskt och aerodynamiskt. Det aerodynamiska ljudet uppstår när rotorbladen passerar luften. Det har en svischande karaktär med en modulation som gör det urskiljningsbart från bakgrundsljudet. Den här delen av vindkraftljudet har visat sig vara mest störande.

I fältstudier genomförda bland människor boende i närheten av vindkraftverk fann man ett samband mellan ljudnivå och bullerstörning, men störningen påverkades också av visuella faktorer som attityden till vindkraftverkens påverkan på landskapsbilden. Andelen störda av buller var högre än vad som tidigare funnits i studier av trafikbuller. Det finns inga vetenskapliga bevis för att buller med de nivåer som vindkraftverk ger upphov till skulle kunna orsaka hälsoproblem andra än störning.

Det gick inte att hitta några studier som behandlade buller från vindkraftverk i vildmark, men effekten av andra bullerkällor såsom flyg har studerats. I friluftsområden är förväntningen på tystnad hög hos besökarna, men vindkraftverk är till skillnad från flyg en stationär källa och kan undvikas av besökarna. Det visuella intrycket av vindkraftverken kan därför vara den dominerande källan till störning.

Regler för buller från vindkraftverk baseras på olika principer. I några länder, t.ex. i Danmark, finns en speciell lagstiftning för vindkraftverk, medan man i andra, som Sverige, använder rekommendationer ursprungligen framtagna för en annan bullerkälla. Gränsvärdet för buller kan antingen vara absolut, som i Tyskland, eller relateras till bakgrundsljudets nivå. Ljudnivån i bakgrundsljudet kan vara standardiserad, mätt eller relaterad till vindstyrka.

1. Introduction

The aim of this study is to summarise present knowledge on noise perception and annoyance from wind turbines in areas where people live or spend time for recreational purposes. This review will also present examples of legislation regarding noise from wind turbines. The study was financed by the Swedish Environmental Protection Agency to form a base for regulation regarding wind turbine noise. Kerstin Persson Waye has 1995 reviewed noise annoyance from wind turbines [Persson Waye 1995]. The present study will recall some of her results, but focus on articles published from 1995 and later.

Noise from wind turbines is a relatively new noise source in Sweden. It can be classified as an outdoor source of community noise. WHO defines community noise as noise emitted from all noise sources except at occupational settings [Berglund et al 1999]. This includes for example road, rail and air traffic, industries, construction and public work as well as neighbours.

This study does not examine the measurements and calculations of noise exposure used in various studies. As many assumptions, on for instance sound pressure levels causing annoyance or sleep disturbance, are based on dose-response relationships were the dose were either measured or calculated (or both) this is a crucial point. This is though a matter of acoustics and not within the subject of this review.

2. Method

Reviewed articles were searched for in relevant databases (Medline, SveMed, ISI, Science direct, Papers First) as well as in journals relevant for the topic. As these searches did not result in many articles, proceedings from well-known conferences have been searched in addition. One must bear in mind that this latter type of papers has often been accepted to conferences without closer examination. As a complement, Internet was searched. Direct contacts with researchers and developers have been made regarding health aspects and noise regulations.

3. Results

3.1 Noise sources from wind turbines, sound characteristics and masking possibilities

There are two main types of noises from a wind turbine: mechanical noise and aerodynamic noise. Mechanical noise is mainly generated by the gearbox, but also by other parts such as the generator [Lowson 1996]. Mechanical noise has a dominant energy within the frequencies below 1000 Hz and may contain discrete tone components. Tones are known to be more annoying than noise without tones, but both the mechanical noise and tones that may occur can be reduced efficiently [Wagner et al 1996]. In the turbines erected during the last ten years, the manufacturers have been able to reduce the mechanical noise to a level below the aerodynamic noise. This is also due to the fact that the size of the turbines has increased and mechanical noise does not increase with the dimensions of turbine as rapidly as aerodynamic noise.

The aerodynamic noise from wind turbines originates mainly from the flow of air around the blades and therefore the noise generally increases with tip speed. It is directly linked to the production of power and therefore inevitable [Lowson 1996]; even though it could be reduced to some extend by altering the design of the blades [Wagner et al 1996]. The aerodynamic noise has a broadband character and is typically the dominating part of wind turbine noise today.

When listening to a wind turbine, one may distinguish broadband noise and a beating noise. Broadband noise is characterised by a continuous distribution of sound pressure. The beating noise is amplitude modulated, i.e. the sound pressure level rises and falls with time. This noise is of interest for this review, as it seems to be more annoying than a non-modulated noise at the same sound pressure level. Only a few studies have however explicitly compared noises with and without modulations. In one experimental study, it was found that a 30 Hz tone, amplitude modulated with a modulation frequency of 2.5 Hz, generally caused higher annoyance, symptoms and change in mood, however the difference compared to a non-modulated tone at 30 Hz was only statistically significantly different for subjective reports of drowsiness [Persson et al 1993]. It has also been found that annoyance caused by diesel trains decreases when the modulation depth was reduced over time from 13 dB to 5 dB [Kantarelis and Walker 1988]. Modulated noise from wind turbines has the beat of the rotor blades' pace. The amplitude modulation has in experimental studies found to be most apparent in the 1 and 2 kHz octave band with amplitude of ± 2-3 dB [Dunbabin 1996]. Theories have been put forward regarding the source and extent of the amplitude modulation. One possible mechanism is the interaction of the blade with disturbed airflow around the tower, another the directionality of radiation from the blades as they rotate. Finally it is possible that variation in noise levels occur due to the atmospheric wind profile, which would result in a slight variation in angel of attack as the blade rotates [Dunbabin 1996]. In summery, the modulation in the noise from wind turbines is not yet fully explained and will probably not be reduced in the near future and is therefore a factor of importance when discussing noise annoyance from wind turbines.

The modulation frequency for a three-blade 600 kW turbine, a common size in Sweden today, with a steady speed of 26 rpm is 1.3 Hz. This is a frequency somewhat lower than the frequency of 4Hz known to be most easily detected by the human ear [Zwicker and Feldtkeller 1967]. The amplitude of the modulation does not have to be very high. The threshold for detection of a sound with a modulation frequency of 1 Hz was in one experimental study found to be 1-2 dB below a masking noise (white noise). The masking noise had its energy within the same frequency band as the modulated sound, thus providing optimal possibilities for masking. It was also found that the detection threshold was not depending on modulation depth or modulation frequencies (1Hz and 10 Hz) [Arlinger and Gustafsson 1988]. The new turbines erected today often have variable rotor speed. This means that the modulation frequency will be low at low wind speed, typically 0.5 Hz at 4 m/s and higher at high wind speed, typically 1.0 Hz at 20 m/s. This is still in the span were modulations could easily be detected. A lower modulation frequency is preferable, as it will then be less detectable and also most likely less annoying. It is however not known how much less annoying these types of turbines will be.

In experimental studies, where 25 subjects were exposed to five different wind turbine noises at the level of 40 dBA Leq, differences between the noises regarding annoyance were found [Persson Waye and Öhrström 2002]. The most annoying noises were predominantly described as "swishing", "lapping" and "whistling". These adjectives could all be seen as related to the aerodynamic noise and as descriptions of a time varying (modulated) noise with high frequency content.

In summery it can be concluded that the modulating characteristics of the sound makes it more likely to be noticed and less masked by background noise. Recent reports have indicated yet another complication. Common hub height of the operating wind turbines today in Sweden is 40-50 meters. The new larger turbines are often placed on towers of 80 – 90 meters. The wind speed at this height compared to the wind speed at the ground might (up to now) been underestimated. In a report published by Rijksuniversiteit Groningen it was found that the wind speed at 80 meter was 4.9 times higher then at 10 meter at night instead of 1.4 times as calculated [Kloosterman et al 2002]. The study was rather small, but indicates that the masking of the background noise is lower than calculated. Further studies need to be performed.

Topographical conditions at site have importance for the degrees to which the noises from wind turbines are masked by the wind. Dwellings that are positioned within deep valleys or are sheltered from the wind in other ways may be exposed to low levels of background noise, even though the wind is strong at the position of the wind turbine [Hayes 1996]. The noise from the turbine may on these conditions be perceived at lower sound pressure levels then expected. Current recommendation state that measures and sound propagation calculations should be based on a wind speed of 8 m/s at 10 meter above the ground, down wind conditions, creating a "worst case" scenario. This recommendation does not consider the case described above.

3.2. Perception and noise annoyance from wind turbines in living areas

Noise from wind turbines can be more or less distinguished depending on the difference between noise from the wind turbine and the background noise. The background noise, for example traffic noise, noise from industries and the whistling in bushes and trees, vary from site to site, but also from day to night. The local environment at the dwelling could also cause a difference in wind speed between the wind turbine and the listener. An example of topographical conditions enlarging the differences in wind speed was described in chapter 3.1. Also less extreme local physical circumstances, as the placing of houses, may shelter the site from wind on the ground, lowering the background noise so that the noise from the wind turbine will be more easily heard.

Only few field studies on noise annoyance among people living close to wind turbines have been carried out. A major study, partly financed by the European Community, was performed in Denmark, the Netherlands and Germany in the beginning of the 1990's [Wolsink et al 1993]. Results from the Danish part of the study were analysed further and presented in a separate report [Holm Pedersen and Skovgard Nielsen 1994]. A Swedish dose-response study was performed 2000 [Pedersen and Persson Waye 2002]. The three studies all explore the correlation between noise exposure from wind turbines (dose) and the noise annoyance among the residents (response), as well as other variables of importance for annoyance. Unfortunately none of these studies has yet been published in refereed journals.

In the European study presented by Wolsink et al [1993], sixteen sites in the three countries comprising residents living within noise levels of 35 dBA were selected. As a certain variance had to be included in the study, residence living at sound pressure levels <25dBA to 60 dBA were chosen, though the major portion or 70% lived within noise levels of 30-40 dBA. The sites comprised a total of 134 turbines: 86 in the Netherlands, 30 in Germany and 18 in Denmark. Most of the turbines were small. Only 20 of them had a power of 500 kW, all the rest were of 300 kW or less.

The results presented were based on a total of 574 interviews: 159 in the Netherlands, 216 in Germany and 199 in Denmark. The response rate is not known. A questionnaire including questions on noise (annoyance, perceived loudness and interference), attitude to wind power, residential quality and stress were used for the interviews. Sound pressure levels were measured on sites, but how these measurements were made is not clear. Sound pressure level strata were calculated with 5 dBA intervals.

Only a weak correlation between sound pressure level and noise annoyance caused by wind turbines could be found (Kendall's coefficient for correlating rank order variables $t=0.09$; $p<0.05$). The proportion annoyed by noise from wind turbines was 6.4% (n=37). The perceived loudness was also low, as well as the interference of noise with various daily activities. Residents complaining about wind turbines noise perceived more sound characteristics ($t=0.56$; $p<0.001$) and reported more interference of daily activities ($t=0.56$; $p>0.001$). The noise produced by the blades lead to most complaints. Most of the annoyance was experienced between 16.00 p.m. and midnight.

Wolsink et al (1993) also evaluated other physical variables and their relation to noise annoyance, e.g. distance between residence and the wind turbine site, location with regard to wind direction, other buildings or natural barriers between the residence and the wind turbine. When adding these variables to the analysis, the objectively measured sound pressure level was no longer significantly related to noise annoyance. Other variables, both subjective and objective, were tried in a multivariate analyse of the level of annoyance of noise from wind turbines. Four variables had an impact of noise annoyance: stress caused by wind turbine noise, daily hassles, perceived effects of wind turbines in the landscape (visual intrusion) and the age of the turbine site (the longer it has been operating, the less annoyance). These four variables explained 53% of the variance of noise annoyance. Variables that had no impact on noise annoyance in the model were e.g. buildings between the residence and the wind turbine or objective sound pressure level. The results should be treated with caution, as the actual level of annoyance among the large majority of the subjects was low.

The Danish part of the study was, as mentioned, presented in a separate report. The 18 wind turbines on the selected sites were rather small; i.e. they had a power of 45 kW to 155kW. The hub height ranged from 18 to 33 meters, with a median of 23 meters. Interviews with 200 residents were performed. The questions agreed on in the European study were used, as well as additional questions. The survey was masked to the respondents as a study on general living conditions. The response rate is not known. A number of objective variables were linked to each respondent, e.g. distance and direction to nearest wind turbine, barriers between residence and turbine, trees or bushes that could mask the noise and a variable called visual angle. The visual angle was measured in degrees from the respondents dwelling to the hub with the ground as the horizontal line. This variable was included as a measure of visual impact. Several noise variables were also added. Sound pressure levels were measured on a ground board at a distance of 1-2 times the hub-height behind the turbine at the same time as the wind was measured at 10 meters height in front of the turbine. Sound pressure levels for each dwelling were then calculated in two ways; not including the influence of barriers and including the influence of barriers. Both reflect downwind conditions at 5 and 8 m/s. The sound was also analysed for tones.

The proportion rather annoyed by noise from wind turbines was 7% (n=14) and the proportion very annoyed was 4% (n=4). The annoyance increased with increasing sound pressure level. At Lr=40dBA (calculated LpA and 5dB added to for audible tones) the mean annoyance was 0.25 at a scale from 0 to 10. Comparing this with the distance and the visual angle, the distance should exceed 300 meters and the visual angle should be less than 3.5 degrees if the annoyance should be kept below 0.25. The angle 3.5 degrees correspond approximately to a distance from the dwelling to the turbine of 16 times the hub-height. A linear regression showed that the objective variable that had the greatest impact on noise annoyance was the visual angle that explained 12% of the variance. Of the variables describing sound properties, the once including LpA (A-weighted sound pressure level) and Lr (5dB added to LpA for audible tones), were also of importance, but to a lesser extend. There was no difference when the sound was calculated for 5 m/s or for 8 m/s. The visual angle and the variables describing sound properties were in turns correlated to each other. Subjective variables were also tried in a linear regression, which showed that whether the turbine noise could be heard or not had the greatest impact on noise annoyance and explained 49% of the variance. Three other subjective variables were also of importance: perception of shadows (r^2=0.23), perception of flicker (r^2=0.25) and the attitude to the turbines' impact on the landscape (r^2=0.23). All these are visual. The conclusion of the authors of the Danish study was that both sound pressure level and visual variables have an impact on noise annoyance.

The Swedish study was performed in Laholm during May-June 2000. The areas chosen comprised in total 16 wind turbines thereof 14 had a power of 600 kW. The study base comprised one randomly selected subject between the ages of 18 and 75 in each household living within a calculated wind turbine sound pressure level of 25 to 40 dBA (n=518).

The annoyance was measured using a questionnaire. The purpose of the study was masked and among questions on living conditions in the countryside, questions directly related to wind turbines were included. Annoyance from several outdoor sources was asked for regarding the degree of annoyance both outdoor and indoor. Annoyance was measured with a 5-graded verbal scale ranging from “do not notice” to “very annoyed”. The same scale was used for measuring annoyance from wind turbines specifically (noise, shadows, reflections, changed view and psycho-acoustical characters). The respondents' attitude of the impact of wind turbines on the landscape scenery and the attitude to wind power in general were also measured with a 5-graded verbal scale, ranging from “very positive” to “very negative”. Questions regarding living conditions, health, sensitivity to noise and employment were also included. A total of 356 respondents answered the questionnaire, which gave a total response-rate of 69%.

For each respondent calculated A-weighted sound pressure level as well as distance and direction to the nearest wind turbine were obtained. Sound pressure levels (dBA) were calculated at 2.5-decibel intervals for each household. The calculations were done in accordance with [Naturvårdsveket 2001] and reflect downwind conditions. Data of distance between the dwelling of the respondent and the nearest wind turbine, as well as the direction, was obtained from maps.

The correlation between noise annoyance from wind turbines and sound pressure level was statistically significant (r_s=0.399; n=341; $p<0.001$). The annoyance increased with increasing sound pressure level at sound pressure levels exceeding 35 dBA. No respondent stated them selves very annoyed at sound pressure levels below 32.5 dBA (Figure 1). At sound pressure levels in the range of 37.5 to 40.0 dBA, 20% were very annoyed and above 40 dBA 36%. The confidence intervals were though wide; see Figure 1.

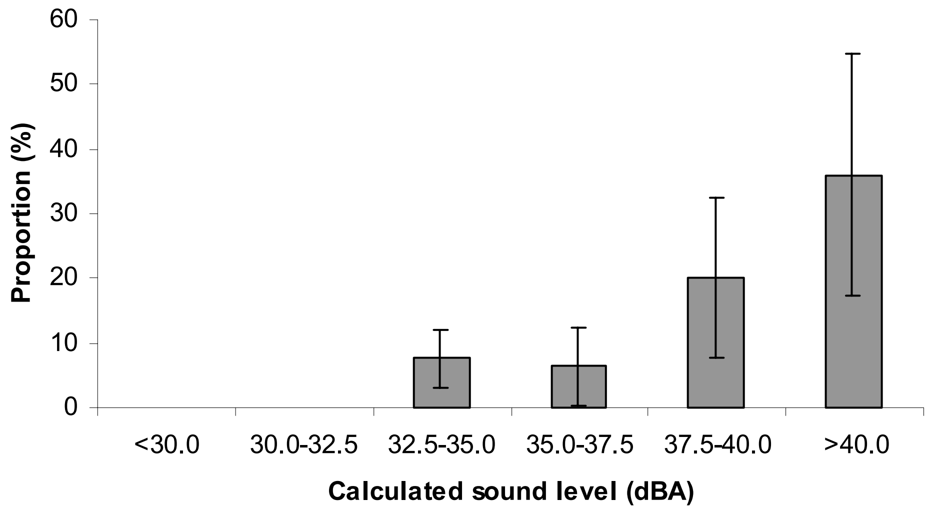

Figure 1. The proportions very annoyed by noise outdoors from wind turbines (95%CI) at different A-weighted sound pressure levels [Pedersen and Persson Waye 2002].

To explore the influence of the subjective factors on noise annoyance, binary multiple logistic regression was used. The analysis showed that the odds for being annoyed increased with 1.87 (95% CI: 1.47-2.38) for each 2.5 dBA increase in sound pressure level. After correction for the individual subjective factors: attitude of visual impact, attitude to wind power in general and sensitivity to noise, the odds for being annoyed decreased to 1.74 (95% CI: 1.29-2.34) for each 2.5 dBA increase in sound pressure level. Only attitude of visual impact had a significant influence on the risk. There was also a statistically significantly correlation between noise annoyance and annoyance of shadows from wind turbines (r_s=0.491; n=339; p<0.001) as well as annoyance of changed view (r_s=0.461; n=340; p<0.001).

The respondents were asked to rate the perception and annoyance of noise from the rotor blades and the noise from the machinery. Noise annoyance from rotor blades and machine were positively correlated to sound pressure level, (r_s=0.410; n=339; p<0.001) and (r_s=0.291; n=333; p<0.001) respectively. At all sound pressure levels, a higher proportion of respondents noticed sound from rotor blades than from the machinery. The same proportion that noticed sound from wind turbines in general noticed sound from the rotor blades. Among those who could notice sound from wind turbines, swishing (33.3%, n=64), followed by whistling (26.5%, n=40) and pulsating/throbbing (20.4%, n=31), were the most common sources of annoyance regarding sound properties.

The proportion rather and very annoyed by noise from wind turbines was small in the first two studies presented above. The annoyance increased with increasing sound pressure level, but the correlation was low. Unfortunately there is no information about proportion annoyed at different sound pressure levels. These percentages would have been interesting to compare with the result of the Swedish study, as the result of this study was different from the results in the two first studies regarding dose-response correlation. In the Swedish study, the proportion very annoyed from wind turbine noise was rather high at sound pressure levels exceeding 37.5 dBA, and a firm correlation between sound pressure level and annoyance was found. All studies find a relation between noise annoyance and visual factors such as visual intrusion and shadows. These factors probably explain part of the noise annoyance. All three studies were performed among residents exposed to rather low sound pressure levels from wind turbines. Still annoyance occurred to some extent. In the noise, the aerodynamic part was found to be the most annoying, stressing the relevance of the sound characteristic, which is also in accordance with previous experimental studies [Persson Waye and Öhrström 2002].

3.3 Perception of noise from wind turbines in wilderness recreational areas

The special soundscape[1] of wilderness recreational areas has been described by a number of authors, e.g. [Miller 2001, Dickinson 2002]. The soundscape differs from site to site and can be very quiet in remote areas, especially when vegetation is sparse (as in the Swedish bare mountain region). In a comparison between different outdoor settings in USA, it was found that the sound pressure level in a suburban area at nighttime was above 40 dBA, along a river in Grand Canyon 30-40 dBA and at a remote trail in the same park 10-20 dBA [Miller, 2002]. The effect of intruding sound should be judged in relation to the natural ambient soundscape. The sound pressure level of the intruding sound must be compared to the sound pressure levels of the background noise. The durability of audibility is another variable of importance for understanding visitors' reactions to noise [Miller 2001].

No studies on noise from wind turbines in wilderness areas have to my knowledge been carried out, but the effect of noise from other sources has been discussed in a few articles. A larger study on noise annoyance from aircraft over-flights on wilderness recreationists was performed in three wilderness areas in USA [Fidell et al 1996]. The areas were chosen specifically for their expected relatively large number of aircraft over-flights. On-site interviews regarding noise annoyance were conducted among visitors. The response rate was 96% (n=920). In addition, more than 2000 h of automated, A-weighted sound pressure level measurements were made as well as forty-six hours of recordings. Out of these, day-night average sound pressure levels (DNL) of visitors' total noise exposure and their exposure to indigenous sound for the time-period of interviewing were estimated.

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[1] One definition of soundscape can be found in "The Handbook for acoustic ecology", Truax, B. (ed) R.C. Publications, Vancouver, Canada. 1978. "SOUNDSCAPE: An environment of sound (sonic environment) with emphasis on the way it is perceived and understood by the individual, or by a society. It thus depends on the relationship between the individual and any such environment."

Table 1. Prevalence of annoyance and estimated cumulative exposure to aircraft noise [Fidell et al 1996]

	%Highly annoyed[2]	Aircraft DNL	Ambient DNL	Total DNL
Golden Trout	12	50 dB	47 dB	52 dB
Cohutta	2	47 dB	52 dB	53 dB
Superstition	1	34 dB	38 dB	39 dB

The results showed that the large majorities (75%-92%) of respondents were not annoyed[3] by noise of over-flights in the three wilderness areas studied. A minority (1%-12%) was highly annoyed. Aircraft that typically produced higher noise levels (low flying jets and helicopters) or operated at shorter slant ranges from observers were reported to be more annoying than small propeller driven aircraft and high altitude jet transports. Little evidence was found that over-flights diminished respondent's overall enjoyment of their visits, nor their intention to return for additional visits. Other aspects of wilderness visits than noise annoyance were of more importance to the visitors than noise from aircraft, e.g. inadequate trail maintenance, crowding, insects and weather. The study was followed up with a telephone survey among visitors from nine wilderness areas in addition to the three selected for the first study. The results were on the whole the same. Fidell and co-workers compared their data with a theoretically derived dosage response relationship between the prevalence of annoyance in residential setting and exposure to general transportation noise. This suggested that respondents engaged in outdoor recreation in three wilderness areas included in the study described themselves as highly annoyed by 7 dB less aircraft noise exposure than would be tolerable in a residential setting.

A quasi-experimental field study on aircraft noise in recreational areas was performed in Norway [Aasvang and Engdahl 1999]. Two groups of people (n=10, n=16) were exposed to aircraft noise in a recreational area close to Fornebu Airport in Oslo and asked to rate their annoyance of noise during a 45-minute section. At the same time the number of over-flights and noise levels were measured. The correlation between noise exposure and annoyance was statistically significant. Of interest for this review is the rating of acceptable annoyance that the subjects were asked to do. Comparing the acceptance with the noise exposure in a linear regression, 50% of the subjects in group-1 considered the noise as not acceptable at sound pressure levels above 60 Laeq (dB). In group-2, who were exposed to less discernible noise events and lower noise levels due to different wind conditions, 50% did not accept sound pressure levels above 50 Laeq (dB). One should be aware of the small number of subjects in each group. Noticeable is that the background noise level for the first group was 40.2 Laeq (dB) and for the second group 42.6 Laeq (dB). Aasvang and Engdahl discussed several explanations of the different outcomes of the two groups. One suggestion was that air flight approach operations are more annoying than departures, even though they resulted in lower sound pressure levels. Due to wind conditions, the exposure of group 2 was dominated by approach operations.

2 The definition of highly annoyed used in this study has not been found.
3 The definition of not annoyed used in this study has not been found.

Another Norwegian study on aircraft disturbance was carried out as an on-site study in a recreational mountain area [Krog et al 2000]. Daily over-flights were planned together with the Norwegian Air Force so that hikers would be exposed to aircraft noise at different level and different frequency. Interviews with visitors were performed near the end of a walking trail. The purpose of the study was masked, i.e. the study was presented as a general survey about outdoor recreation. A total of 761 respondents participated in the survey. The response rate is not known. Of the respondents exposed to over-flights (n=386), 56% found the aircraft noise very disturbing. When dividing the exposed into four different groups, according to which flying pattern they were exposed to, no differences between the rates of annoyance could be found between the groups. The results also showed that the disturbance due to military aircraft noise increased with increasing age, increasing total noise exposure and increasing duration of time spent on the hike. However, there was no significant difference between the exposed and the unexposed group regarding the overall satisfaction with today's hike. Among the exposed subjects, it was found that the more negative evaluation of military aircraft noise, the higher the likelihood to judge the hike as less positive.

Staffan Hygge has recently in a report for the Swedish National Rail Administration (Banverket) and National Road Administration of Sweden (Vägverket) summarised studies on noise annoyance in recreational areas and national parks [Hygge 2001]. Though the overall proportion of annoyed by aircraft noise is low in many studies, the individual factors are of importance for annoyance. For visitors who seek quietness just hearing any sound from aircraft could be bothering. Hygge also discusses possible cultural differences in acceptance of noise in recreational areas. American studies show a lower proportion of annoyed than studies from Norway and New Zealand. This could be due to the fact that that the non-American studies were done in remote areas which presumable gives a group of respondent with a special profile, seeking quietness. He also discusses other sources of transportation noise and finds an indication that the legitimacy is of importance, e.g. rescue flights are more accepted than sightseeing tours.

Aircraft over-flight is a mobile source of noise in contrary to noise from wind turbines, so the two cannot directly be compared. Noise from wind turbines is more similar to noise from ski lifts. The noise source is stationary and the visitors can usually choose themselves if the like to stay by the noise or move on. Ski lifts are operating at special hours in the winter and they can be assumed to produce noise at comparable sound pressure levels when they are operating. Wind turbines are operating all year around, day and night, but the sound pressure levels vary with the wind and noise is only produced at special conditions.

Some results from the aircraft studies could though be transferred. The expectation of quietness is high among visitors and Fidell et al [1996] estimated that the noise level tolerated in wilderness areas compared to residential areas was 7 dBA lower. The tolerance also depended on the legitimacy of the noise source. Cultural differences in accepting noise should also be discussed. If there were a cultural difference in how noise in recreational areas is accepted, the tolerance would probably be low in Sweden. The visual effect of the wind turbines may be a source of annoyance equal to noise in recreational areas, especially if there is large wide-open space.

3.4 Aspects of health and well-being

According to the definition made by WHO, health is a state of complete physical, mental and social well-being and not merely the absence of infirmity. The WHO Guidelines for Community noise lists specific effects to be considered when setting community noise guidelines: interference with communication; noise-induced hearing loss; sleep disturbance effects; cardiovascular and psycho-physiological effects; performance reduction effects; annoyance responses; and effects on social behaviour [Berglund et al 1999]. Interference with communication and noise-induced hearing loss is not an issue when studying effects of noise from wind turbines as the exposure levels are too low.

No studies have been found exploring cardiovascular and psycho-physiological effects, performance reduction effects and effects on social behaviour specifically with regard to noise from wind turbines. A number of articles have though explored the relationships between exposure of other sources of community noise (road traffic, aircraft, railway traffic) and health effects. Evidence in support of health effects other than annoyance and some indicators of sleep disturbance is weak [Berry et al 1998]. In a Swedish official report Öhrström reviews the effects of community noise in general [Öhrström 1993]. On basis of studies on effects of noise from aircraft and road traffic, she finds that there are some evidences of noise causing psychosocial or psychosomatic nuisance. The effects are related to individual factors (sensitivity to noise and capacity to cope with stress) and to annoyance rather than to sound pressure level. Annoyance itself is though an undesired effect of health and well-being. In a review of studies performed 1993-1998, Lercher et al [1998] evaluated adverse physiological health effects of occupational and community noise. Most of the studies concern sources of noise with higher sound pressure levels than those of wind turbines. Even so, it was difficult to find correlation between exposure and e.g. cardiovascular or immunological effects. In a summery of possible long term effect of exposure to noise done by Passchier-Vermeer the observed threshold for hypertension and ischaemic heart disease was 70 dBA outdoors [Passchier-Vermer 2002]. Transferring the results of these studies, there are no evidences that noise from wind turbines could cause cardiovascular and psycho-physiological effects. However, the overall effect for people living in the vicinity of a wind turbine should be considered (noise annoyance, visual annoyance). The European field study mentioned above indicates that wind turbines could cause stress [Wolsink et al 1993]. Stress is not defined in the report and could be just another aspect of annoyance, but stress could also be one health variable that needs to be investigated further.

Annoyance response is probably the most studied health effect regarding wind turbines. As outlined in chapter 3.2 and 3.3, noise annoyance appears even at low sound pressure levels. Another health effect that may be relevant for people living near wind turbines is sleep disturbance. The WHO guidelines for community noise recommend that the outdoor noise levels in living areas should not exceed 45 dBA Leq at night, measured with the time base 8 hours [Schwela 1998], as sleep disturbance may occur with open windows. The exposure from wind turbines is not known to exceed this limit, but in the Swedish field-study mentioned above [Pedersen and Persson Waye 2002], of the 12 respondents at exposure level 37.5-40.0 dBA who stated them selves disturbed in their sleep by noise, 10 respondents mentioned wind turbines as source. Almost all of them slept with open window. The number of respondents was however too low for conclusions to be drawn and further research is needed.

In a review of health effects of road traffic noise, Rylander finds that there is no research done so far that indicates that environmental noise could provoke psychiatric disease [Rylander 1999]. Noise as a factor of stress, inducing symptoms among sensitive individuals is discussed, as well as the possibility of noise interacting with other environmental strains causing stress. Further research is though needed.

Summarising the findings, there is no scientific evidence that noise at levels emitted by wind turbines could cause health problems other than annoyance. However, sleep disturbances should bee further investigated. As noise from wind turbines has a special characteristic (amplitude modulation, swishing) it may be easily detected in a normal background noise and this may increase the probability for annoyance and sleep disturbance. The combination of different environmental impacts (intrusive sounds, visual disturbance and the unavoidance of the source in the living environment) could lead to a low-level stress-reaction, which should be further studied.

3.5 A comparison of noise regulations in European countries

A summary of limits and regulations regarding noise from wind turbines in some European countries was done by Lisa Johansson in the notes from an IEA topical expert meeting in Stockholm [Johansson 2000]. Her summary has here been updated and expanded.

The recommended highest sound pressure level for noise from wind turbines in Sweden today is 40 dBA outside dwellings (Naturvårdsverket webbplats). In noise sensitive areas as in the mountain wilderness or in the archipelago, a lower value for the highest sound pressure level is preferable. The penalty for pure tones is 5 dBA. In praxis, the sound pressure levels at dwellings nearby a planned wind turbine site are calculated according to [Naturvårdsverket 2001] during the process of applying for a permission to build. Measurements in site are only performed in case of complains and then as measurements of imission at the dwelling of the complainant at wind speeds of 8 m/s at 10 m height.

Denmark has a special legislation governing noise from wind turbines (Bekendtgørelse om støj fra vindmøller BEK nr 304 af 14/05/1991). The limit outside dwellings is 45 dBA and for sensitive areas 40 dBA Leq. Sensitive areas are areas planned for institutions, non-permanent dwellings or allotment-gardens, or for recreation. In case of complaints emission measurements are performed according to the legislation, i.e. on a plate on the ground at a distance of 1-2 times the hub height of the turbine. Noise imission at the dwelling of the complainant is then calculated.

The legal base for noise pollution in Germany is the Federal clean air act from 1974 (Bundes-Immissionschultz-Gesetzes. BimSchG, Germany, 1974). The limited values for the sound pressure levels are defined in TA Lärm (Technische Anleitung Lärm, Germany, 1998).

Table 2. German noise regulations

Area	Day	Night
Industrial Area (Industrigebeit/Gewergebeit)	70 dBA / 65 dBA	70 dBA / 50 dBA
Mixed residential area and industry Or Residential areas mixed with industry	60 dBA	45 dBA
Purely residential areas with no commercial developments (Allgemeines Wohngebeit/Reines Wohngebeit)	55 dBA / 50 dBA	40 dBA / 35 dBA
Areas with hospitals, health resorts, etc.	45 dBA	35 dBA

Calculation of sound propagation is done according to DIN ISO 9613-2. All calculations have to be done with a reference wind speed of 10 m/s at 10 m heights[4].

The French legislation used in the case of wind turbines is the neighbour noise regulation law (Loi n° 92-1444 du 31 décembre 1992: Loi relative à la lutte contre le bruit). This legislation is based on the principle of noise emergence above the background level and there is no absolute noise limit. The permitted emergence is 3 dBA at night and 5 dBA at day. The background noise level has to be measured at a wind speed below 5 m/s. The legislation is not adjusted to wind turbine cases, and in praxis the noise measurements are made at 8 m/s when the wind turbine noise is expected to exceed the background noise levels the most[5].

New regulations on noise including noise from wind turbines were introduced in the Netherlands 2001 (Besluit van 18 oktober 2001, houdende regels voor voorzieningen en installaties; Besluit voorzieningen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487). The limits follow a wind speed dependent curve. For the night the limit starts at 40 dBA at 1 m/s and increases with the wind speed to 50 dBA at 12 m/s. For daytime the limit starts at 50 dBA and for evenings at 45 dBA.

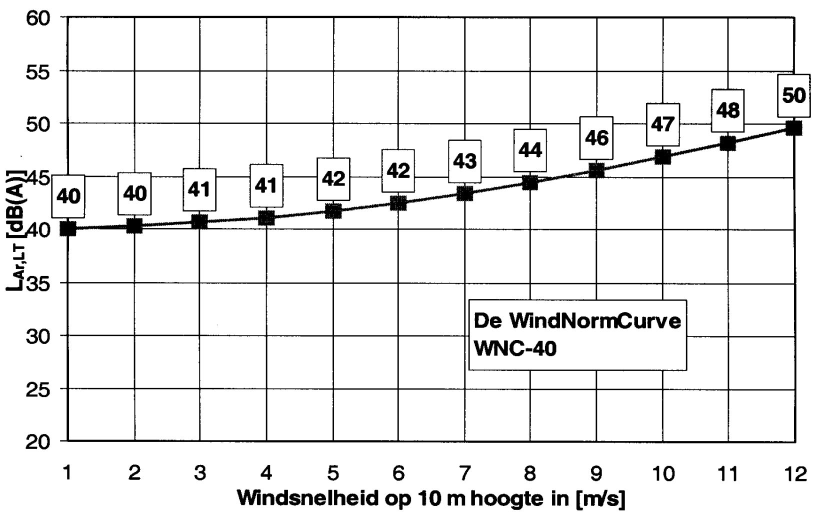

Figure 2. De WindNormCurve. Besluit van 18 oktober 2001, houdende regels voor voorzieningen en installaties; Besluit voorzieningen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487. Bijlage 3.

4 Correspondence with Pamela Ljungberg, Enercon.

5 Correspondence with Karina Bredelles, consultant at ABIES, France

In Great Britain the ETSU-report "The assessment and rating of noise from wind farms" (ETSU for DTI 1996) is referred to by for instance the Scottish Executive Development Department (PAN 45). The report presents a series of recommendations that is regarded as relevant guidance by the authorities. Generally noise limits should be set relative to the background noise and only for areas for which a quiet environment is desirable. More precisely, noise from wind farms should be limited to 5 dBA above background noise for both day- and night-time. The $L_{A90,\ 10\ min}$ descriptor should be used both for the background noise and for the noise from the wind farm. The argument for this is that the use of the $L_{A90,\ 10\ min}$ descriptor allows reliable measurements to be made without corruption from relatively loud, transitory noise events from other sources. A fixed limit for 43 dBA is recommended for nighttime. This is based on a sleep disturbance criterion of 35 dBA. In low noise environments the daytime level of the $L_{A90,\ 10\ min}$ of the wind farm noise should be limited to an absolute level within the range of 35-40 dBA. The actual value chosen within this range should depend upon the number of dwellings in the neighbourhood of the wind farm, the effect of noise limits on the number of kWh generated, and the duration of the level of exposure.

In summery, these regulations are examples of different principles regarding noise from wind turbines. Some states have a special legislation concerning wind turbines, while others use recommendations. Different descriptors as L_{Aeq} or $L_{A90,\ 10\ min}$ are used. The noise level could either be absolute or related to the background noise level. This background noise level could be standardised, measured or related to wind speed.

4. Conclusions

Noise from wind turbines is not at all as well studied as for instance noise from road traffic. As the number of studies is low no general conclusions could be drawn. However, some indications will be listed here.

The reviewed studies above indicate that annoyance from wind turbine noise

- Is to a degree correlated to noise exposure.
- Occurs to a higher degree at low noise levels than noise annoyance from other sources of community noise such as traffic.
- Is influenced by the turbines' visual impact on the landscape.

Wind turbine noise

- Does not directly cause any physical health problems. There is not enough data to conclude if wind turbine noise could induce sleep disturbance or stress-related symptoms.
- Is, due to its characteristics, not easily masked by background noise.
- Is particularly poorly masked by background noise at certain topographical conditions.

Regulations on noise from wind turbines

- Are based on different principles leading to a heterogeneous legislation in Europe.

No conclusions on wind turbine noise in recreational areas could be drawn as no studies on the subject have been found. Other sources of noise studied as aircraft over flights indicate that noise levels tolerated in wilderness areas compared to residential areas are lower, but there is no evidence that this could be transferred to wind turbine noise.

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Regulation of noise from wind turbines

Sweden
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Report 5308 · August 2003

Noise annoyance from wind turbines – a review

This study summarises present knowledge on noise perception and annoyances from wind turbines in areas were people live or spend recreation time.

Field studies performed among people living in the vicinity of wind turbines showed that there was a correlation between sound pressure level and noise annoyance, but annoyance was also influenced by visual factors such as the attitude to wind turbines impact on the landscape. Noise annoyance was found at lower sound pressure levels than in studies of annoyance from traffic noise.

Regulations on noise from wind turbines are based on different principles. Some states have a special legislation concerning wind turbines, while others use recommendations. Different descriptors as L_{Aeq} or $L_{A90,\ 10\ min}$ are used. The noise level could either be absolute or related to the background noise level. This background noise level could be standardised, measured or related to wind speed.

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Investigation, Prediction and Evaluation of Wind Turbine Noise in Japan

Hitomi KIMURA[1]; Yoshinori MOMOSE[1]; Hiroya DEGUCHI[1]; and Mimi NAMEKI[1]

[1] Ministry of the Environment, Japan (MOEJ)

1-2-2 Kasumigaseki Chiyoda-ku, Tokyo 100-8975 JAPAN

ABSTRACT

While increasing in size and number, wind turbines in Japan are often located in quiet rural areas due to the country's lack of shallow adjacent sea and geographically unbalanced wind energy. Since a quiet environment makes wind turbine noise more noticeable, this location of wind turbines sometimes raises complaints about noise by neighborhood residents even if the noise generated by wind turbines is not very loud.

The Ministry of the Environment of Japan has developed an interim report on investigation, prediction and evaluation methods of wind turbine noise based on recent scientific findings, including the results of nationwide field measurements and related surveys in Japan. The challenges to be addressed are also identified.

Keywords: Wind turbine noise, investigation method, reference level
I-INCE Classification of Subjects Number(s): 14.5.4

1. Introduction

It is an important aspect of Japan's energy policy to accelerate the introduction of renewable energy. Among renewable energy sources, wind power generation is one of the important energy sources which emits neither air-polluting substances nor greenhouse gases and can also contribute to energy security because it can be done in Japan. The Basic Energy Plan of Japan (Cabinet decision in April, 2014) regards wind power generation as an energy source which can be made economically viable as its generation cost can be as low as that for thermal power generation if it can be developed on a large scale.

The number of wind power facilities installed in Japan started to increase around 2001, and 2,034 units have been installed by 2014 (as of the end of March, 2015) (1). According to the Supplementary Materials for the Long-term Energy Supply and Demand Outlook issued by the Agency for Natural Resources and Energy in July, 2015, approximately 10 million kW of wind power is expected to be installed by 2030, which represents a nearly four-fold increase from the existing installed wind power capacity of approximately 2.7 million kW (2).

[1] OTO@env.go.jp

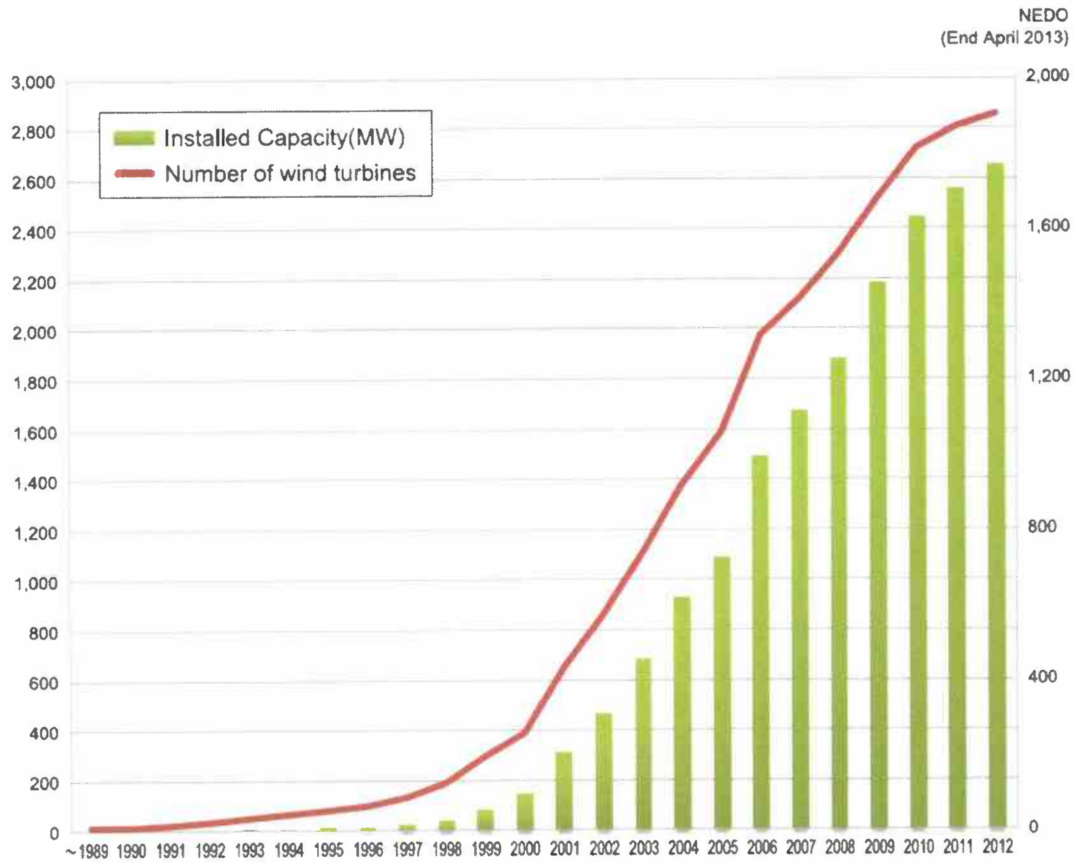

Figure 1. Installed Capacity and Number of Wind Turbines in Japan (Source: NEDO)

On the other hand, wind power facilities emit a certain amount of noise due to their power generation mechanism in which blades rotate by catching wind to generate power. While the noise level is normally not significantly large, there are cases where even a relatively low level of noise causes complaints as wind power facilities are often constructed in agricultural/mountainous areas which are originally quiet due to the need to choose areas which have suitable weather conditions including wind direction and velocity,. There have been not only noise complaints but also complaints of inaudible sound whose frequency is 20 Hz or less.

Against such a backdrop, as a result of the amendment of the Order for Enforcement of the Environmental Impact Assessment Act in October, 2012, the establishment of wind power stations came to be classified as relevant projects under the Act and discussions on the environmental impact assessment of wind power facilities have taken place. However, there are acoustic characteristics peculiar to noise generated from wind power facilities (hereinafter, "wind turbine noise"). It is thus necessary to develop methods relevant to the investigation, prediction, and assessment of wind turbine noise based on the latest scientific findings.

The Ministry of the Environment of Japan has set up an academic expert committee and examined ideas and issues about methods for investigating, predicting, and assessing wind turbine noise in Japan from 2013 to 2016, in light of the results of investigations and studies in Japan published so far as well. This paper reports the interim summary of the examination at the academic expert committee.

2. Extant findings

Surveys measuring wind turbine noise conducted in Japan from 2010 to 2012 revealed the following.

- In terms of spectral characteristics, wind turbine noise generally has a spectral slope of -4 dB per octave. Its 1/3 octave band sound pressure level in all parts of the super-low frequency range, which means 20Hz or lower, is below the ISO threshold of hearing for pure tones and the criterion curve for the assessment of low frequency noise proposed by Moorhouse et al. (Fig. 2). Super-low frequency range components of wind turbine noise are at imperceptible levels. Therefore, wind turbine noise is not an issue caused by super-low frequency range.
- In regard to the audible frequency range, in the range from about 40 Hz and above, the 1/3 octave band sound pressure level is above the said criterion curve and the threshold of hearing defined by ISO 389-7. Therefore, wind turbine noise should be regarded as "audible" sound (noise) in discussing it.

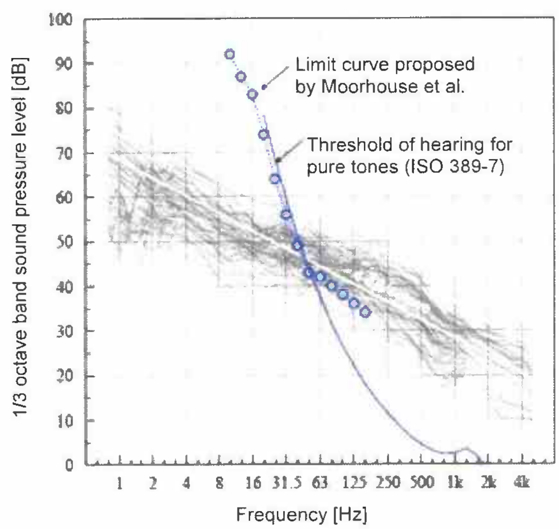

Figure 2. Result of the analysis of frequency characteristics of wind turbine noise (at 164 locations in the vicinity of 29 wind power facilities in Japan)

- Noise exposure levels of nearby residents from wind power facilities are distributed in the range of 26–50 dB in time-averaged A-weighted sound pressure levels. While this implies that wind turbine noise is not significantly higher than other types of environmental noise, it can cause serious annoyance to residential areas in the vicinity of wind power facilities located in extremely quiet agricultural/mountainous areas.
- In Japan, it is empirically known that the following relation holds between L_{Aeq}, which properly excludes non-relevant noise, and L_{A90}: $L_{Aeq} \fallingdotseq L_{A90}+2$ dB

It is also generally said that acoustic isolation is not always effective for noise from wind power facilities because it contains more low-frequency components. In a quiet environment with little noise of other types, it is relatively more easily heard than ordinary noise is.

3. Methods for investigating and predicting wind turbine noise, a perspective for its assessment, and responses against it

In light of the findings described in section 2, the issue of wind turbine noise should be taken not as one of super-low frequency sound below 20 Hz but as one of "audible" sound (noise), and it should be basically measured at the A-weighted sound pressure level. We here summarize matters to be noted in conducting an investigation and/or prediction of noise before and after installing wind power facilities and a perspective for wind turbine noise assessment.

3.1 Investigation and prediction before installation

3.1.1 Matters to be noted upon an investigation

In selecting a method for investigation, it is necessary to collect various kinds of information in light of business and regional characteristics to a necessary extent in order to conduct prediction and assessment appropriately. Particularly with regard to wind turbine noise, it is important to distinguish and discuss three major issues:

(1) Sound source characteristics

It is necessary to pay attention to:

- information on the wind power facility concerned, including its specifications, manufacturer, model number, hub height, rotor diameter, rated wind velocity, and power generation;
- the sound power level of the generated noise;
- the A-weighted overall value and frequency characteristics (including the 1/3 octave band sound power level) of the sound power level at the rated (maximum) output (to grasp the situation of maximal environmental impact);
- A-weighted overall values and frequency characteristics (including the 1/3 octave band sound power level) of sound power levels under different wind velocities;
- pure tonal frequency components (to be determined in accordance with IEC 61400-11:2012); and
- existing data pertaining to the same model in operation.

(2) Propagation characteristics

In Japan, wind power facilities are often installed in agricultural/mountainous areas. Sound waves emitted from a wind power facility installed in an agricultural/mountainous area are affected by various factors before propagating to a sound receiving point (assessment point), in comparison with one installed on a large, flat piece of land such as a plain or desert. Its noise level and frequency characteristics tend to change due to phenomena including reflection, absorption, transmission, refraction, and diffraction. It is therefore necessary to pay attention to:

- phenomena such as the reflection, absorption, or diffraction of wind turbine noise due to undulating terrains or ridges,
- the state of the ground surface (including rivers and lakes), and
- meteorological information such as wind conditions including wind direction, velocity, and frequency.

(3) Information on a sound receiving point (assessment location)

With regard to locations where an investigation is conducted, focusing on the daily life and activities of residents in the vicinity of a wind power facility, it is necessary to pay attention to:

- the configuration of establishments particularly requiring consideration for environmental conservation such as schools and hospitals and the outline of housing configuration (including the structure of each house), and
- the state of the acoustic environment (degree of quietness) of the area in question.

(4) The specific method for investigation

In measuring residual noise in a given area, it is necessary to pay attention to the following.

a. Sound to be excluded

Sounds of the types given below should be excluded. Since wind power facilities operate when wind is blowing, noises caused by wind such as sound of rustling leaves are not excluded. ("Wind noise" generated by wind hitting a sound level meter's microphone is excluded, however.)

i) transitory noise such as the sound of automobiles passing nearby and aircraft noise
ii) artificial sound not occurring regularly such as sound generated by accidents/incidents, vehicles driven by hot-rodders, emergency vehicles, etc.
iii) natural sound not occurring regularly such as sound generated by natural phenomena including rain and defoliation, animals' cries, etc.
iv) sound incidental to measurement such as the voice of a person talking to a measurer, sound of tampering with measuring instrument, etc.

b. Surveying and other equipment

As the wind is generally strong in areas around wind power facilities, it is indispensable to use a windbreak screen in order to avoid effects of wind noise as much as possible in measuring residual noise. Several kinds of urethane spherical windbreak screens with different diameters are commercially available. In general, the larger the diameter of such a screen is, the less likely a sound level meter inside the screen will be affected by wind noise. Installing a windbreak screen can reduce the impact of wind noise up to the wind velocity of around 5 m/s.

c. Survey areas and locations

In light of the propagation characteristics of wind turbine noise, the survey targets areas susceptible to an environmental impact by wind turbine noise, such as residential areas in the vicinity of a wind power facility (generally within a radius of about 1 km from a wind turbine). An area in which a quiet environment should be conserved such as hospital premises may be included in them. In selecting specific survey locations in the survey areas, in addition to locations where a wind power generation facility is planned to be installed, such locations are to be selected that are immune to local impacts of particular sound sources where the average level of noise in the relevant area can be assessed, including residential areas around the wind power generation facility. Measurement is to be performed at an outdoor location 3.5 m or more distant from a reflective object excluding the ground.

d. Survey period and hours

In order to grasp conditions throughout the year accurately, a survey is to be conducted in each period of the year for different typical meteorological conditions under which a wind turbine operates (for instance, each season if meteorological conditions vary greatly by seasons).

The period of a single survey should be appropriately determined in consideration of time variation of noise due to the impact of meteorological conditions and other elements. As measurement values may be unstable depending on wind conditions, a survey should be performed for three or more consecutive days in principle. The survey should be conducted both during the day (6:00–22:00) and at night (22:00–6:00) hours.

3.1.2 Matters to be noted in prediction

As mentioned above, in Japan, wind power facilities are often installed in agricultural/mountainous areas. In comparison with cases where such a facility is installed on a large, flat piece of land such as a plain or desert, sound waves emitted from a wind power facility installed in a mountainous area diffuse in a more complicated manner as they propagate due to the influence of geological states, vegetation, meteorological conditions such as wind conditions, etc. In addition, it has to be noted that the propagation of wind turbine noise is extremely complicated as it is subject to attenuation by distance, reflection and absorption by the ground surface, reflection and diffraction by acoustic obstructions, attenuation by atmospheric absorption, etc.

Among the prediction methods used, while "ISO 9613-2 : 1996" allows incorporation of more detailed conditions, prediction calculation according to it is rather complex. Furthermore, there is a problem of how the reflection rate should be calculated in cases where the effect of reflection by the ground surface becomes an issue, as is the case with a wind turbine installed in a ridge.

On the other hand, the New Energy and Industrial Technology Development Organization (hereinafter, "NEDO") published a prediction method for the environmental impact assessment ofwind power generation in July, 2003 (revised into the second version in February, 2006). This models wind power facilities as sound source points and uses sound power levels provided by manufacturers of wind power generators. This method takes into account distance attenuation due to sound diffusion in the propagation process and attenuation by atmospheric absorption. While this method can be used easily, it is difficult to consider meteorological effects, etc.

It is necessary to pay full attention to such characteristics of methods in making prediction.

3.2 Survey after the installation of a wind turbine

As stated in section 3.1, predicting wind turbine noise involves elements with large uncertainty such as emission characteristics of noise from the source and effects of meteorological conditions as well as terrain and structures in the propagation process. Predicted values before the installation of a wind turbine and measured values after installation may sometimes differ greatly.

We here summarize matters to be noted in a survey after the installation of a wind turbine.

(1) Conditions of measurement

It is necessary to grasp the conditions of measurement and other relevant local matters that may impact the propagation of noise. At least, one should grasp wind direction and velocity at the nacelle height, the variation of power output, and meteorological data required for calculating the attenuation by atmospheric absorption (wind direction and velocity, temperature, and humidity).

(2) Survey method

Wind turbine noise varies greatly by wind conditions, and a wind turbine often starts and suspends operation repeatedly. Therefore, measurement should be performed in appropriate hours in light of the state of operation of the wind power facility in question. For example, a method is conceivable that measures the average level in a 10-minute period in which wind turbine noise is stable (10-minute equivalent noise level: $L_{\mathrm{Aeq,\ 10\ min}}$) and regards it as the representative value. If the relevant wind power facility operates steadily for long hours, it is effective for obtaining robust data, for instance, to measure noise for 10 minutes every hour on the hour and calculate the average energy over the entire period of time.

For measurement locations, period, etc., refer to what is noted for a survey before the installation.

(3) Survey Results

The representative value of a survey after the installation of a wind power facility should be taken as the A-weighted equivalent sound pressure level measured over a period of time in which the effect of wind turbine noise is at its maximum and in which the effect of background noise is low(e.g. during night time). It is also required to confirm whether there is any pure tonal component.

The equivalent noise level during operation can be estimated by adding around 2 dB to the noise level exceeded for 90% of the measurement period (L_{A90}).

3.3 Assessment of wind turbine noise

In assessing the impact of noise resulting from the installation of a facility, the procedure of environmental impact assessment performed before installation examines "whether such noise is avoided or reduced to an extent feasible" and, if applicable, "whether it is intended to be consistent with standards or criteria given by the Japanese government or local municipalities from the perspective of environmental protection."

For the former examination, the extent to which the impact of noise resulting from the implementation of the relevant project is avoided or reduced is assessed by comparing multiple countermeasures in terms of the structure, layout, output, the number of units, and technical noise reduction measures in accordance with the maturity of the project plan. The assessment can also be done by examining to what extent better feasible technology can be incorporated, etc. Specifically, assessment is made from such viewpoints as whether the local noise level will not be significantly raised, whether the layout plan for the project secures a sufficient distance between the facility and residences, etc.

On the other hand, no standards or criteria specific to wind turbine noise have been set from the perspective of environmental protection by the national government.

4. Future agenda

4.1 Actions to be taken by operators and manufacturers of wind power facilities

Operators and manufacturers will continue to be expected to accumulate survey data after the installation of wind power facilities, implement technical measures, such as developing low noise blades or implementing additional soundproof measures, and maintenance measures intended to reduce noise, etc. Furthermore, they are also expected to examine and develop technology supporting the broad promotion of efforts for noise control including the examination of an aerodynamic sound propagation prediction model reflecting locational conditions.

4.2 Actions to be taken by administrative agencies (the government of Japan and local municipalities)

4.2.1 Collecting and sharing information on wind power facilities, raising awareness

It is necessary to develop and improve manuals for appropriately responding to complaints concerning wind power facilities. At the same time, it is necessary to examine a framework for sharing knowledge of technological countermeasures implemented by operators which can be applied to other facilities, to administer education and training programs to enhance local municipality officials' expertise further, to promote understanding by local residents through the dissemination of precise information on the auditory impression of wind turbine noise and similar matters as well as raising their awareness of such information, etc.

It is possible that not only the magnitude and properties of sound but also visual elements are related to complaints about noise from wind power facilities. It is necessary to continue to gather knowledge on the impact of elements other than noise and examine responses.

4.2.2 Perspective for the assessment of wind turbine noise

At present, no standards or criteria specific to wind turbine noise have been set from the perspective of environmental protection by the national government. In light of the fact that wind power facilities are often installed in quiet areas, possible annoyance caused by amplitude-modulation sound (swish sound) and, if applicable, pure tonal components of wind turbine noise, it is necessary to examine a certain reference level for assessment of noise in consideration of the impact on the sound recipients.

Furthermore, with regard to the sound environment in quiet areas, it is necessary to consider all facilities, not limited to wind power facilities, located therein. It is necessary to examine what methods for investigating, predicting, and assessing the sound environment in quiet areas in Japan should be like while surveying examples in other countries.

4.3 Actions to be taken by all parties concerned

When it comes to wind turbine noise, it is important to facilitate communication among relevant stakeholders including operators of wind power facilities, manufacturers, local municipalities, local residents, in light of issues unique to sensory pollution. It has been reported that annoyance caused by wind turbine noise is low among residents who perceive wind turbines positively so that receptivity to the installation of a wind turbine facility is higher among them. There are cases where actions for maintaining a favorable relationship with local residents actually reduced complaints. Such actions include a wind power facility operator's holding briefing sessions, creating an optimal business plan based on the comprehensive analysis of the distance separating residences and the relevant establishment in conjunction with the installation and layout of a wind power facility, continuing to deal with complaints, and concluding an agreement with local residents and municipalities. It is necessary to enhance communication among the parties concerned in this light.

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Manuscript March 1, 2018

On Cuba, Diplomats, Ultrasound, and Intermodulation Distortion

University of Michigan Tech Report CSE-TR-001-18

Chen Yan[1], Kevin Fu[2], and Wenyuan Xu[1]

[1]Department of Systems Science and Engineering, Zhejiang University
[2]Computer Science & Engineering, University of Michigan

March 1, 2018

Abstract

This technical report analyzes how ultrasound could have led to the AP news recordings of metallic sounds reportedly heard by diplomats in Cuba. Beginning with screen shots of the acoustic spectral plots from the AP news, we reverse engineered ultrasonic signals that could lead to those outcomes as a result of intermodulation distortion and non-linearities of the acoustic transmission medium. We created a proof of concept eavesdropping device to exfiltrate information by AM modulation over an inaudible ultrasonic carrier. When a second inaudible ultrasonic source interfered with the primary inaudible ultrasonic source, intermodulation distortion created audible byproducts that share spectral characteristics with audio from the AP news. Our conclusion is that if ultrasound played a role in harming diplomats in Cuba, then a plausible cause is intermodulation distortion between ultrasonic signals that unintentionally synthesize audible tones. In other words, acoustic interference without malicious intent to cause harm could have led to the audible sensations in Cuba.

1 Introduction

This technical report analyzes how intermodulation distortion of multiple inaudible ultrasonic signals could have unintentionally produced audible side effects and harm to diplomats.

In early 2017, diplomats in Cuba suffered hearing loss and brain damage after hearing strange metallic sounds. The news media published reports ranging from scientific analysis of sound recordings [16, 24, 27] to the diplomatic implications [11, 10, 12, 13]. The mystery deepened after physicians published two dueling JAMA papers on neurological damage to diplomats [25, 18]. The news media remained flummoxed on what may have caused the neurological damage [15, 17, 8]. Several news reports suggested that an ultrasonic weapon could have caused the harm. Other experts suggested toxins or viruses. The cause remains a mystery. The substantiated facts include:

- Ultrasonic tones are inaudible to humans.
- Diplomats in Cuba heard audible sounds.

Therefore, any sounds perceived by diplomats are not likely the ultrasound itself. We were left wondering:

1. How could ultrasound create audible sensations?
2. Why would someone be using ultrasound for in the first place?

Assumptions and Limitations. We assume that the sound came from ultrasound, then work backwards to determine the characteristics of the ultrasonic source that would cause the observed audible sensations.

There could be added distortion in the AP audio, so we cannot assume the recordings reflect what humans actually perceived. In one video, the AP news is seen playing a sound file from one iPhone to a second iPhone, essentially making a recording of a recording. Each traversal through a speaker or microphone will add distortion and filtering.

Our experiments focus on spectral properties rather than the effect of amplitude or distance. It might be worthwhile to replicate our experiments with a high powered array of ultrasonic transducers. We do not explore non-ultrasonic hypotheses such as toxins, RF, or LRADs. We also do not consider direct mechanical coupling such as sitting on an ultrasonic vibrator.

Why Ultrasound? It is well known that audible sounds typically propagate omnidirectionally and are difficult to confine to parts of a room. In contrast, ultrasound tends to propagate within a narrower beam than audible sound and can focus a beam towards a more specific area. News reports cited diplomats discussing sounds that were narrowly confined to a room or parts of a room. This type of observation is strongly correlated with ultrasound. We believe that the high-pitched audio signals confined to a room or parts of a room are likely created by ultrasonic intermodulation distortion.

How to Produce Audible Sound from Ultrasound? Humans cannot hear airborne sounds at frequencies higher than 20 kHz, i.e., ultrasound. Yet the AP news reported that "It sounds sort of like a mass of crickets. A high-pitched whine, but from what? It seems to undulate, even writhe." The AP's spectrum plot shows a strong audible frequency at 7 kHz. We believe that this 7 kHz sound is caused by intermodulation distortion, which can down-convert the frequency of ultrasound into the audible range—resulting in high-pitched noises. Nonlinearity typically causes Intermodulation distortion. The engineering question boils down to: assuming an ultrasonic source, how can the audible byproducts consist of a mixture of several tones around 7 kHz separated by 180 Hz?

Sources of Ultrasound. There are many potential sources of ultrasound in office, home, and hotel environments. Energy efficient buildings often use ultrasonic room occupancy sensors in every room (Figure 1). Ultrasonic emitters can repel rodents and other pests. HVAC systems and other utilities with pumps or compressors can vibrate entire buildings. Certain burglar alarm sensors, security cameras, and automated doors use ultrasound for detection of movement.

Researchers from Illinois recently proposed using specially crafted ultrasound to jam microphones [20]. If sounds from an ultrasonic jammer (Figure 2) were to collide with an eavesdropping device attempting to covertly exfiltrate a signal over an ultrasonic carrier, these two signals could combine to produce audible byproducts in both air and microphones. However, if there were an ultrasonic jammer present, it would have likely jammed all nearby microphones, including the microphone used to record the metallic sounds. This would make jammers an unlikely cause.

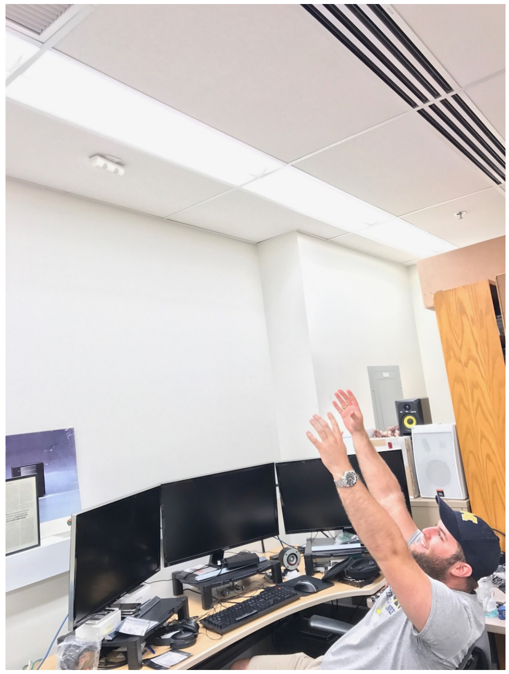

Figure 1: *Michigan Computer Science & Engineering Ph.D. student Connor Bolton notices that an ultrasonic room occupancy sensor in the ceiling had been bathing his experiments with unwanted 25 kHz sounds.*

When introducing additional ultrasonic interferce to an ultrasonic jammer, the signals might render the jammer ineffective while causing unwanted audible byproducts to humans and nearby microphones.

There are also hailing devices such as the Long Range Acoustic Device (LRAD) that many people claim use ultrasound. There may be LRADs that use ultrasound, but modern LRADs tend to use parametric audible sound below 3 kHz. Using an array of several dozen piezo speakers that emit sound in a synchronized fashion to improve directionality, an LRAD can generate sound waves where the wavelength is much smaller than the size of the speaker. Under such conditions (which also tend to be true for ultrasonic emissions), the sound will propagate in a tight, directional beam—allowing long distance delivery of sound.

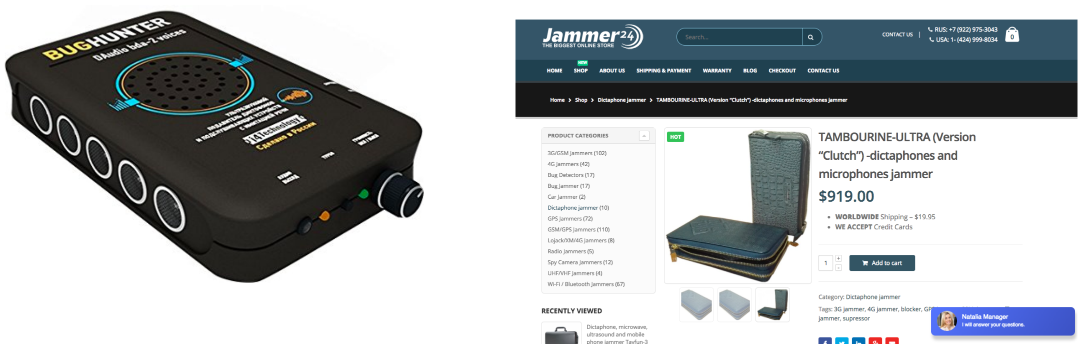

Figure 2: *Commercial products with several ultrasonic transducers can jam nearby microphones. One manufacturer sells a clutch, presumably for fashionable people to jam microphones at cocktail parties.*

2 Spectral Analysis of AP News Audio

We initiate our study with two observations from the AP news: (1) the original audio recordings and (2) description on the high-pitched sounds heard by those in Cuba. Our goal is to construct ultrasonic signals that can lead to similar spectral and audible characteristics.

Audio clips. The AP News [16] published several recordings from Cuba described as high-pitched or metallic cricket sounds[1]. As a common method to analyze signals, frequency spectrum is obtained by Fourier transforms of the original sounds. The AP news performed the spectrum analysis on a smartphone (Figure 3) and shown a spectrum plot centered at 7 kHz (Figure 4 and 5). The spectrum plot demonstrates that there are roughly more than 20 different frequencies embedded in the audio recording.

We acquired the audio from the AP News[2], which claims include a recording of what some U.S. embassy workers heard in Havana. The recording extracted from the video is 5 seconds long, and sampled at 44.1 kHz with 32-bit floats. We analyzed the sound in time (Figure 6), frequency (Figure 7), and time-frequency domains (Figure 8).

After zooming in and looking through the time signal, we found nothing remarkable. No modulation appears in the waveform (at least not ASK), and the waveform does not resemble FSK or

[1] `https://www.apnews.com/88bb914f8b284088bce48e54f6736d84`
[2] https://www.youtube.com/watch?v=Nw5MLAu-kKs

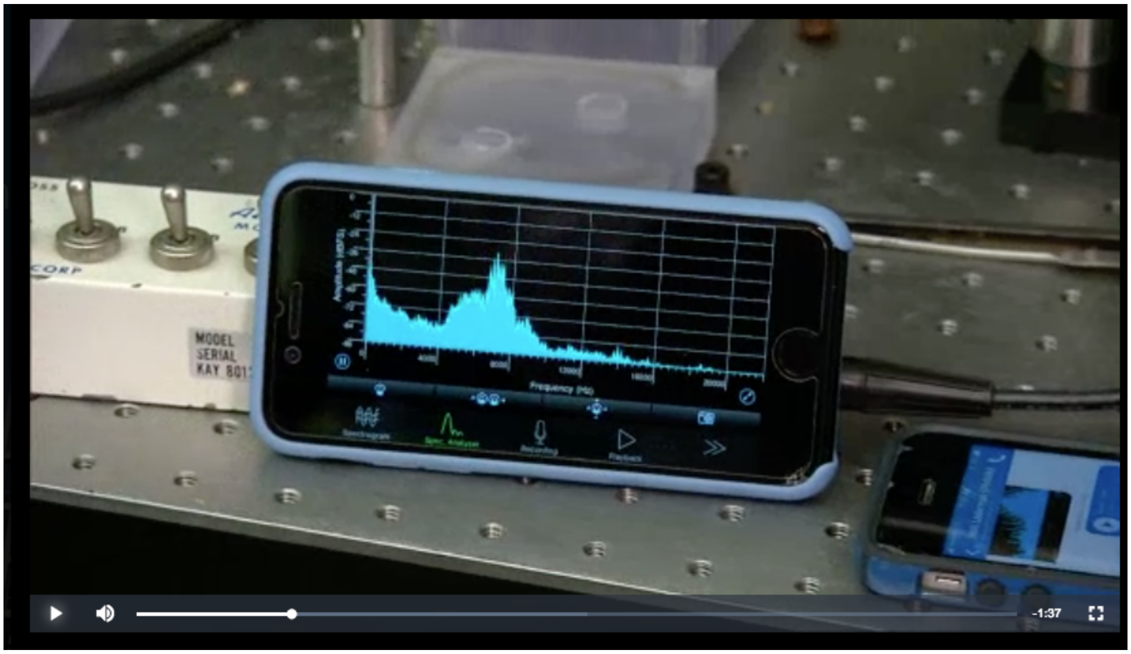

Figure 3: *Screen shot of the AP news itself showing a screen shot of a recording of yet another recording from Cuba. Note that the recording device appears to have removed the spectrum above 14 kHz.*

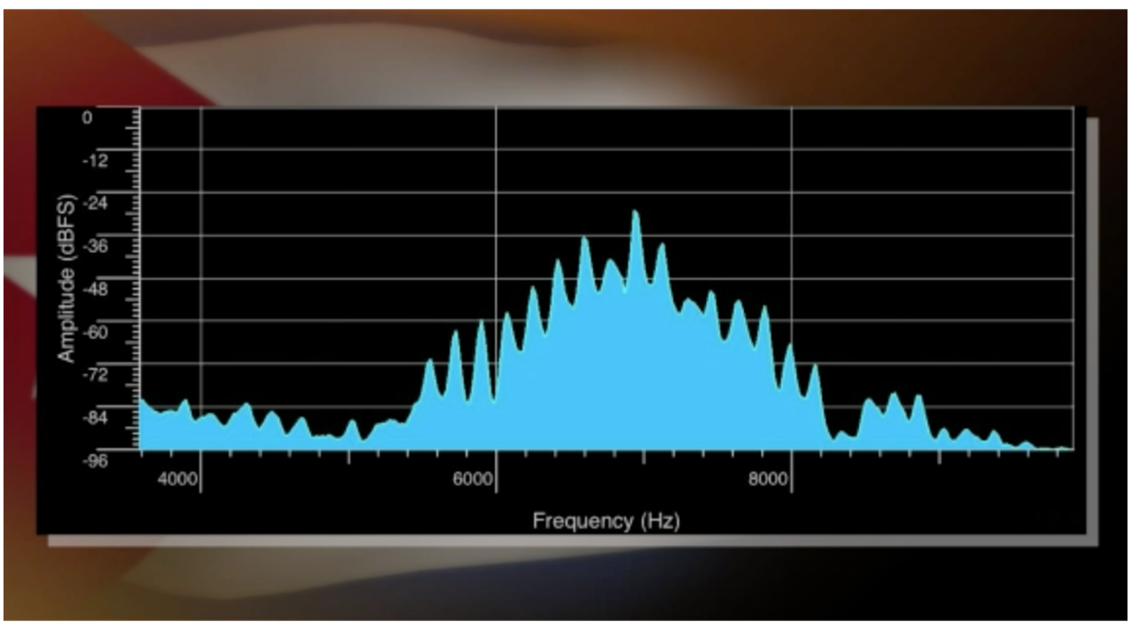

Figure 4: *Screen shot of the AP news showing the Fourier transform of what appears to be a recording of sounds heard in Cuba.*

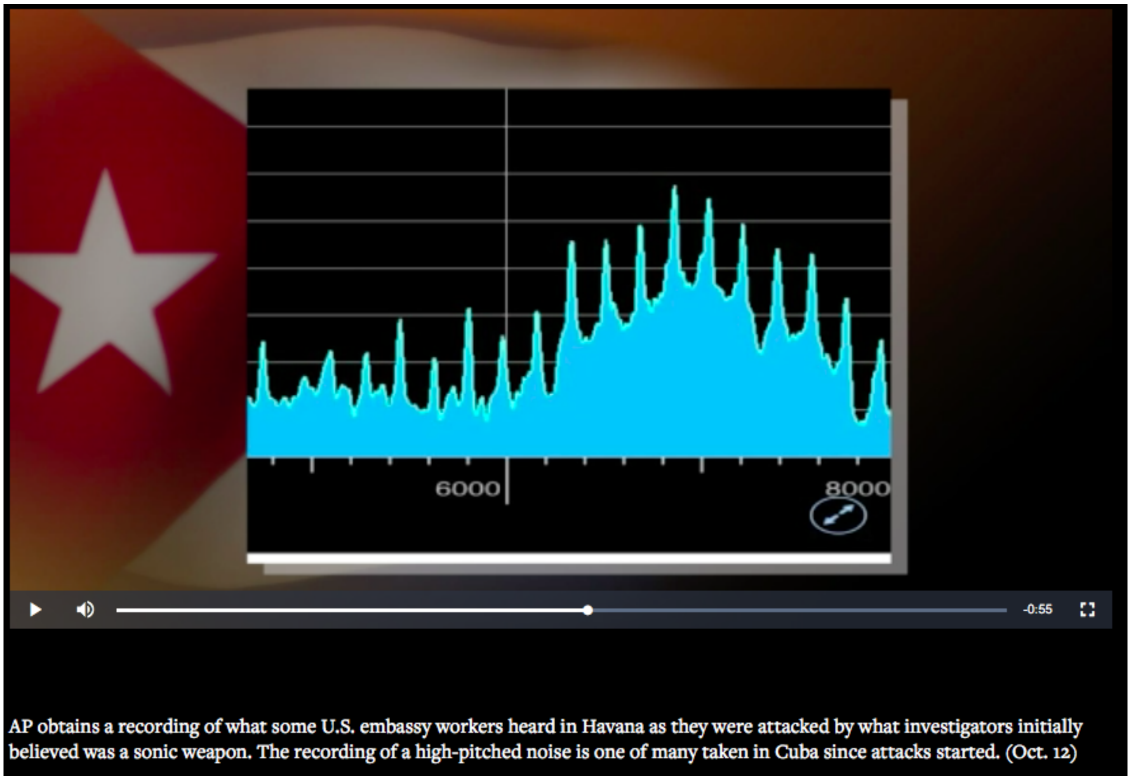

Figure 5: *Screen shot of the AP news analyzing a different recording showing emphasis on spectrum near 7 kHz.*

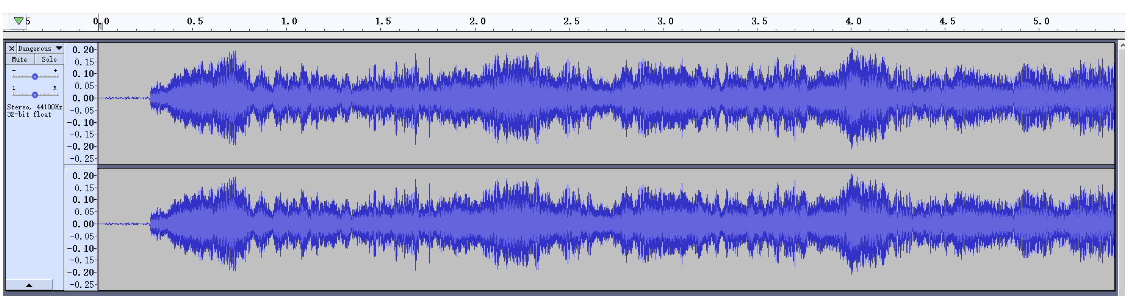

Figure 6: *The time domain signal of metallic sounds extracted from the AP News video.*

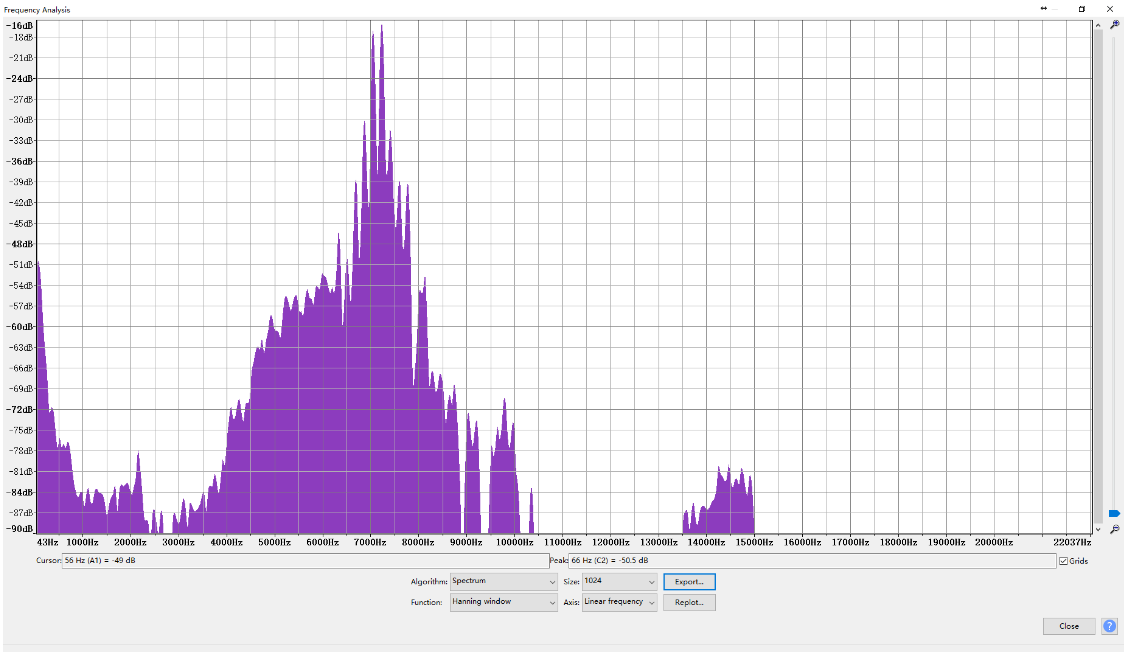

Figure 7: *The spectrum of metallic sounds extracted from the AP News video. The spectrum of the AP news audio ends abruptly at 15 kHz. We suspect this is an artifact of either the AP audio filtering, YouTube audio filtering that is known to roll off beginning at 16 kHz, or iPhone audio filtering that begins to roll off at 21 kHz on our equipment.*

PSK, among other common modulation schemes. We wondered for a moment if someone might be playing a joke on us with fake audio if after demodulation, a message were to tell us it's all a joke. So for giggles, we tried AM demodulation. The resulting signal sounds like a F1 engine and is not likely meant as a message.

The spectral plot (Figure 7) shows major frequency components around 7 kHz. The peaks (6,704 Hz, 6,883 Hz, 7,070 Hz, 7,242 Hz, 7,420 Hz) are separated by approximately 180 Hz.

However, in the waterfall plot (Figure 8), the major frequencies (in yellow) do not change over time. This lack of change again suggests that there is no frequency-related modulation, such as FM or FSK. So wherever the sound comes from, it produces a mixture of several tones around 7 kHz separated by 180 Hz.

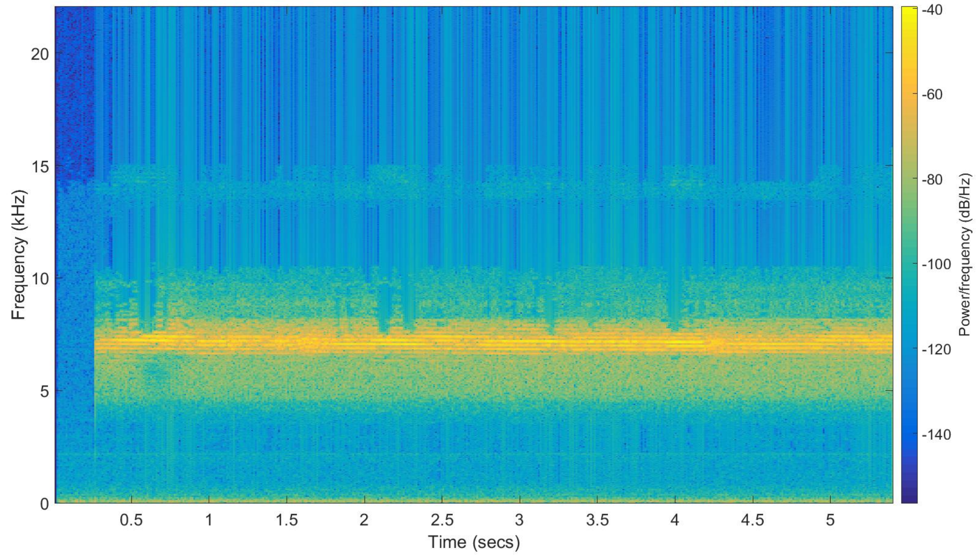

Figure 8: *The spectrogram-time plot (waterfall) of metallic sounds extracted from the AP News video.*

3 Simulation: Intermodulation Distortion of Ultrasound

Intermodulation distortion (IMD) is the result of multiple signals propagating through nonlinear systems. Without loss of generality, a nonlinear system can be modeled as the following polynomial equation:

$$s_{out} = a_1 s_{in} + a_2 s_{in}^2 + a_3 s_{in}^3 + \cdots + a_n s_{in}^n$$

where s_{in} is the system input and s_{out} is the system output. The $a_n s_{in}^n$ for $n > 1$ is called the nth order IMD. When s_{in} contains multiple frequency tones, the IMDs introduce new frequency components.

3.1 Simulation of 20 kHz and 21 kHz IMD

To illustrate the principle of intermodulation distortion independent of what may have happened in Cuba, let $s_{in} = s_1 + s_2$, where $s_1 = \sin(2\pi f_1 t)$ and $s_2 = \sin(2\pi f_2 t)$. When $f_1 = 20$ kHz and $f_2 = 21$ kHz, the spectrum of s_{in} will have two spikes with one at 20 kHz and another at 21 kHz

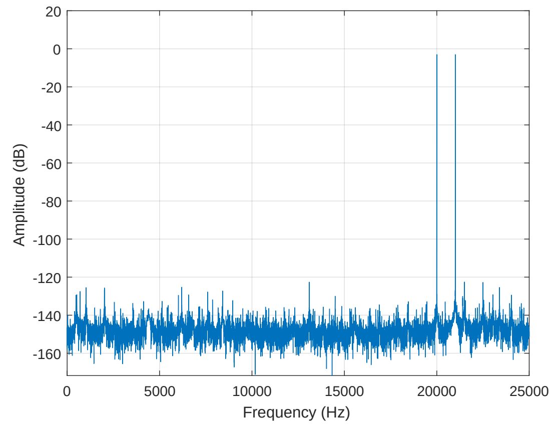

Figure 9: *Spectrum of our input signal with pure tones at 20 kHz and 21 kHz to illustrate effects of IMD in a nonlinear medium.*

(Figure 9).

After the signals pass through the nonlinear system, s_{out} will contain new frequency components that are determined by the order of IMD. Figures 10–11 show the spectrum of the 2nd, 3rd, 4th, and 5th IMDs. For example, the 2nd order IMD introduces new frequencies at $f_2 - f_1$ (1 kHz), $f_2 + f_1$ (41 kHz), $2f_1$ (40 kHz), and $2f_2$ (42 kHz). Notice that $f_2 - f_1$ is below 20 kHz and audible. The 4th order IMD introduces both $f_2 - f_1$ (1 kHz) and $2f_2 - 2f_1$ (2 kHz).

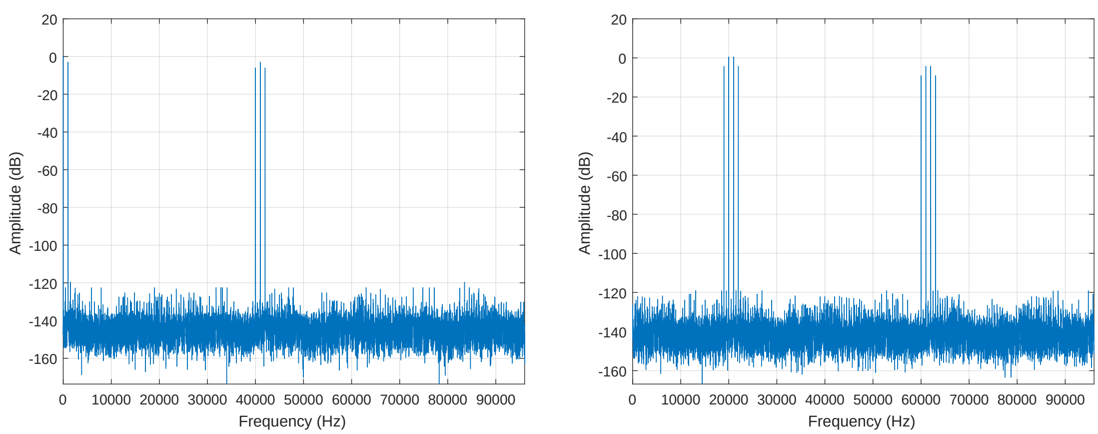

Figure 10: *Spectrum of the (L) 2nd and (R) 3rd order IMD for* $(f_1, f_2) =$ *(20 kHz, 21 kHz).*

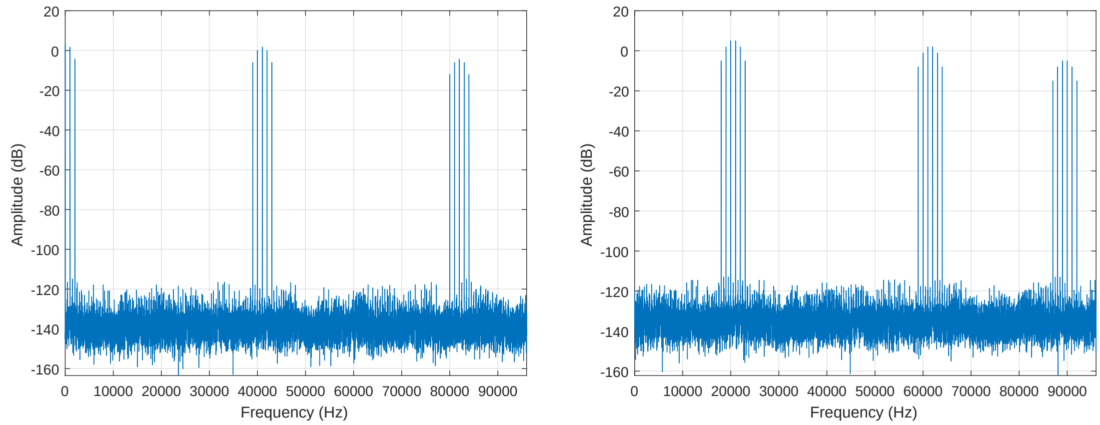

Figure 11: *Spectrum of the (L) 4th and (R) 5th order IMD for* $(f_1, f_2) =$ *(20 kHz, 21 kHz).*

3.2 Simulation of IMD of Three Ultrasonic Tones

In practice, most signals contain multiple tones. To illustrate the effects of IMD on three ultrasonic tones, let us explore the case of three signals at 25 kHz, 32 kHz, and 32.18 kHz. That is, $s_{in} = s_1 + s_2 + s_3$, where $s_1 = \sin(2\pi f_1 t)$, $s_2 = \sin(2\pi f_2 t)$, and $s_3 = \sin(2\pi f_3 t)$, $f_1 = 25$ kHz, $f_2 = 32$ kHz, and $f_3 = 32.18$ kHz. We selected 32.18 kHz to mimic the observation of a 180 Hz separation in the AP news spectrum.

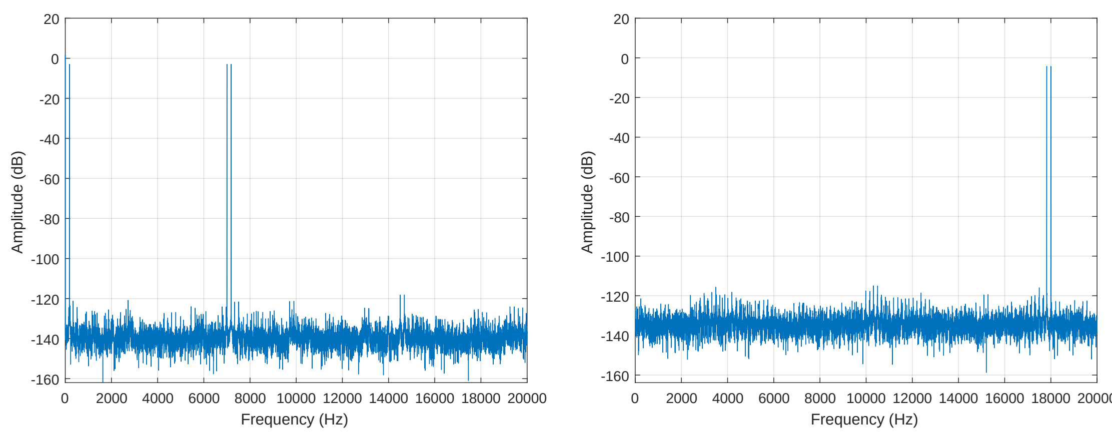

Figure 12: *Audible spectrum of the (L) 2nd and (R) 3rd order IMD for 25 kHz, 32 kHz, and 32.18 kHz tones.*

When there are more than two signals, intermodulation happens between each pair of the signals. In our case, the 2nd order IMD introduces new frequencies (below 20 kHz) at $f_2 - f_1$

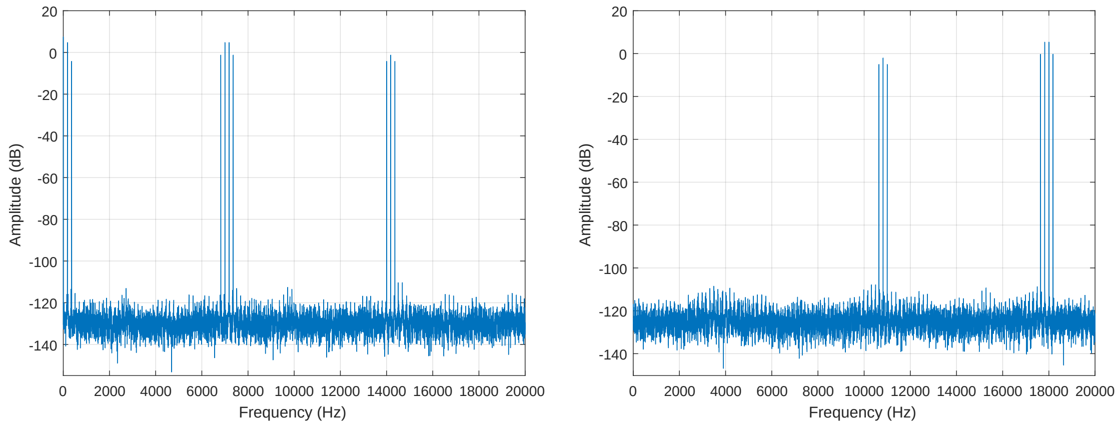

Figure 13: *Audible spectrum of the (L) 4th and (R) 5th order IMD for 25 kHz, 32 kHz, and 32.18 kHz tones.*

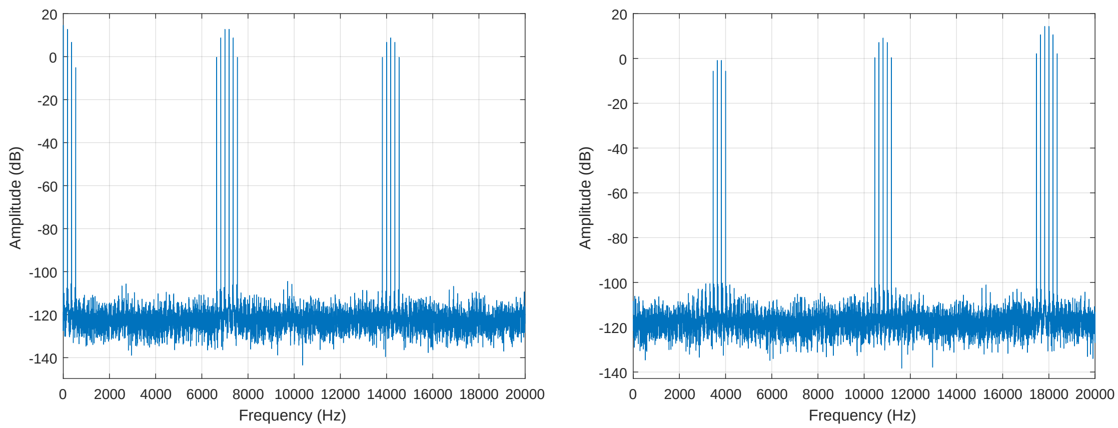

Figure 14: *Audible spectrum of the (L) 6th and (R) 7th order IMD for 25 kHz, 32 kHz, and 32.18 kHz tones.*

(7 kHz), $f_3 - f_2$ (180 Hz), and $f_3 - f_1$ (7.18 kHz). If there are more signals (e.g., another $f_4 = 31.82$ kHz), more IMD products are generated — $f_4 - f_1$ (6.82 kHz), and $f_3 - f_4$ (360 Hz), and existing IMD frequencies are enhanced ($f_2 - f_1$ (180 Hz)). The higher order IMD products (4th, 6th, 8th, etc.) will generate more frequencies around the existing ones (7 kHz and 180 Hz) with a separation of 180 Hz, and create new frequencies. For example, the 4th order IMD introduces new frequencies (below 20 kHz) at $f_3 - f_2$ (180 Hz), $f_3 - f_2$ (360 Hz), $2f_2 - f_3 - f_1$ (6.82 kHz), $f_2 - f_1$ (7 kHz), $f_3 - f_1$ (7.18 kHz), $2f_3 - f_2 - f_1$ (7.36 kHz), $2f_2 - 2f_1$ (14 kHz), $f_2 + f_3 - 2f_1$ (14.18 kHz), and $2f_3 - 2f_1$ (14.36 kHz). With the increase of IMD orders, there will be more frequency peaks

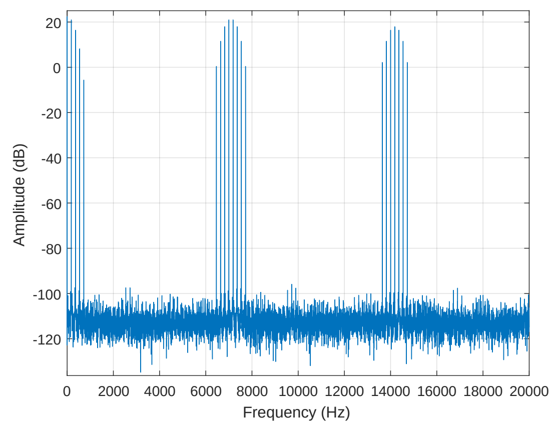

Figure 15: *Audible spectrum of the 8th order IMD for 25 kHz, 32 kHz, and 32.18 kHz tones.*

rippling around 180 Hz, 7 kHz, and 14 kHz. Each ripple will be separated by 180 Hz.

Now consider the audible frequencies produced by all the IMDs up to and including the 8th order summed together in Figure 16. The peaks near 7 kHz are beginning to resemble the AP news spectrum.

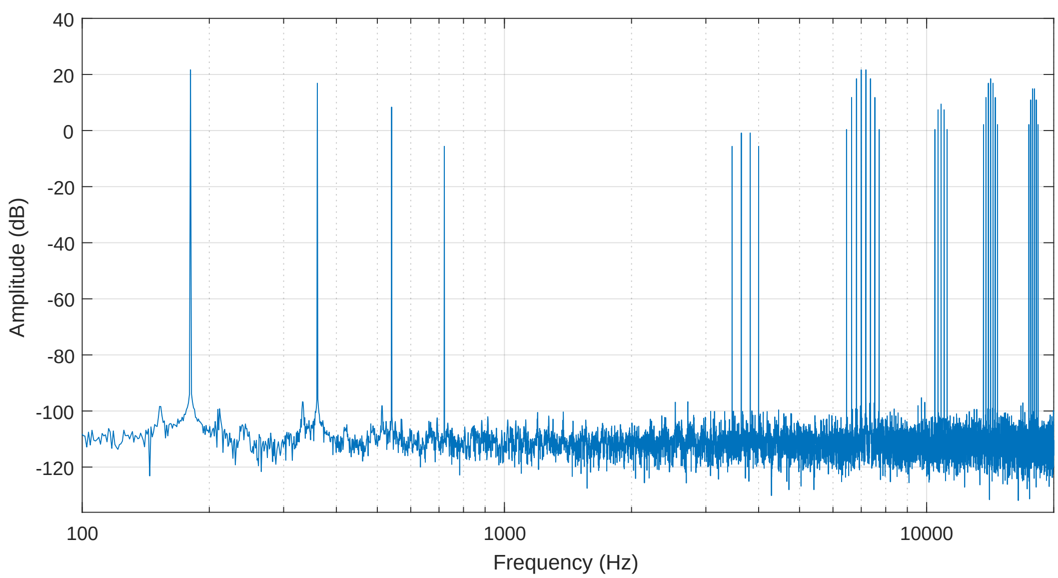

Figure 16: *Log-scale cumulative audible spectrum of 2nd though 8th order IMD for 25 kHz, 32 kHz, and 32.18 kHz.*

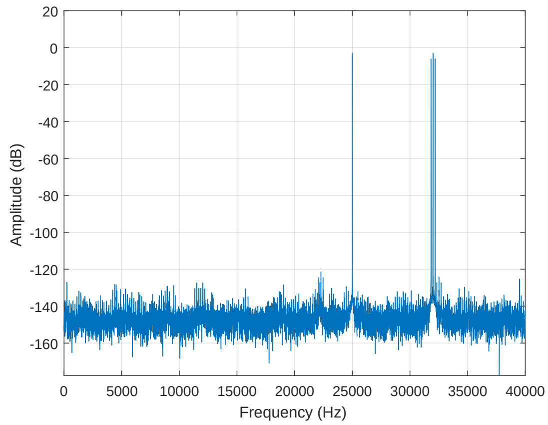

Figure 17: *Calculated spectrum of 25 kHz tone and 180 Hz AM modulated over a 32 kHz carrier.*

3.3 Simulation of IMD of Ultrasonic Modulation

To generate similar intermodulation of three ultrasonic tones, it is feasible to explore the IMD for two signals where one is modulated on an ultrasonic carrier. In particular, to generate signals similar to the recording, i.e., signals centered at 7 kHz with a serial of multiples of 180 Hz signals nearby, we can utilize two signals and their intermodulation. Let $s_{in} = s_1 + s_2$. One of the signals can be a single tone, $s_1 = \sin(2\pi f_1 t)$, and the other will be a signal that is modulated with a single tone of 180 Hz. In particular, we utilize amplitude modulation (AM) that produces double-sideband and transmitted carrier. For example, when the baseband signal is a single tone at $f_m = 180$ Hz, and the carrier signal is at $f_c = 32$ kHz, AM with transmitter carrier will produce an output of $s_2 = \sin(2\pi f_c t) + \sin(2\pi f_c t)\sin(2\pi f_m t)$, which can be seen as the combination of three signals at f_c (32 kHz), $f_c + f_m$ (32.18 kHz), and $f_c - f_m$ (31.82 kHz), as shown in Figure 17. When IMD happens between such an AM signal and a $f_1 = 25$ kHz single tone, the result will be exactly the same as the previous example — signals around 7 kHz, 180 Hz, 14 kHz, and more.

The spectrum of the simulated IMD through the 7th order products with input of 25 kHz and 180 Hz AM modulated on a 32 kHz carrier is depicted in Figure 18 and Figure 19 (log-scale).

If the baseband signal is not a 180 Hz tone, but music or something else with many tones, it will only change the separation (f_m) of the smaller peaks. The recovered signals always remain at around 7 kHz, 14 kHz, and 18 kHz. If we only consider the strongest 2nd order product, there will

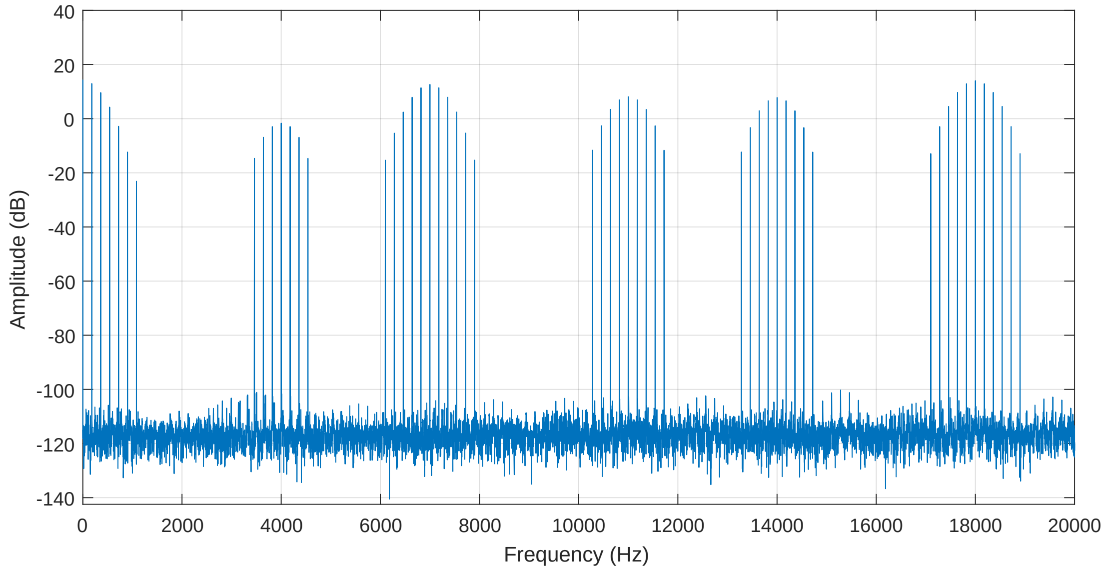

Figure 18: *Cumulative audible spectrum of 2nd though 7th order IMD for 25 kHz tone and 180 Hz AM modulated over a 32 kHz carrier.*

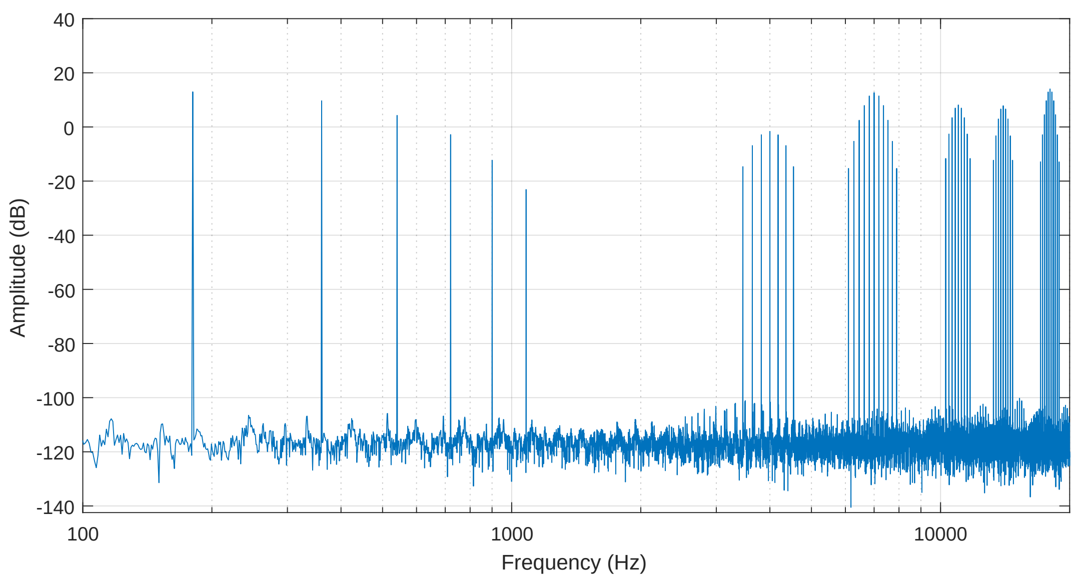

Figure 19: *Log-scale cumulative audible spectrum of 2nd though 7th order IMD for 25 kHz tone and 180 Hz AM modulated over a 32 kHz carrier.*

be signals at only around 7 kHz.

3.4 Discussion of Simulation Results

Different systems (e.g., recording devices) have different nonlinear properties that determine the strength of each order of IMD products. In the simulations, we use a_i coefficients of unity weight for the strengths. If we were to obtain the recording devices and emitters from Cuba, we could deduce the coefficients. We surmise that the reason that there are no obvious frequencies at 4 kHz, 11 kHz, and 18 kHz in the original AP news recording is because the intermodulation products at the odd orders are weak relative to the 2nd and 4th order IMDs on whatever devices recorded sounds in Cuba.

The IMD can also happen multiple times. IMD may occur during air-borne transmission. The IMD can happen again inside the circuitry of a microphone as well as in the human inner ear itself. Thus, the perceived sounds will differ depending upon where one is listening and what are the characteristics of the microphone.

3.5 Summary of IMD Simulation

Our simulations confirmed the feasibility of reproducing the acoustic spectrum of the AP news recording with the intermodulation distortion of multiple ultrasonic signals. Notice that in the spectrum of the AP news recording, there were also frequency components at 180 Hz (not obvious), 360 Hz, 540 Hz, and around 14 kHz.

4 Experiments

With the theories validated by the Matlab simulations, our next step was to generate real ultrasonic signals that caused audible sensations that mimic the sounds heard in Cuba.

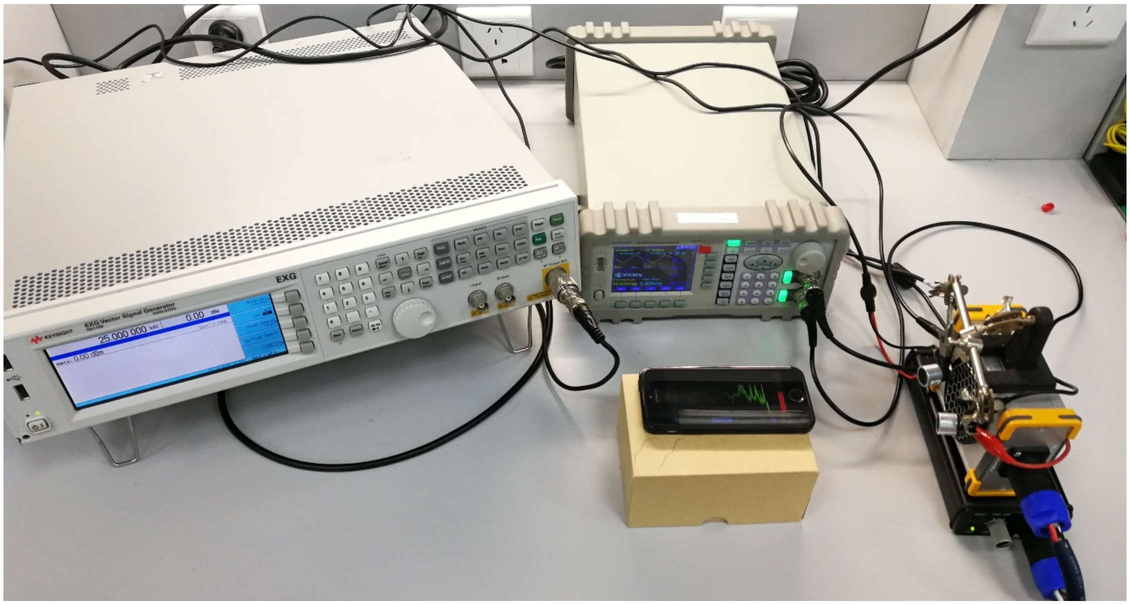

Figure 20: *Our benchtop equipment to carry about the proof of concept reproduction of tones heard in Cuba. Note, we would expect emitters to be smaller than a paperback book in practice, if not smaller. We use large equipment because of our general-purpose laboratory.*

4.1 Experimental Setup

Our experiments tested several different emitters and frequencies. We primarily use one wide-band ultrasonic speaker in combination with a multitude of fixed ultrasonic transducers to artificially create IMD. Our fixed transducers are centered at 25 kHz or 32 kHz depending on the experiment. Each fixed transducer has enough tolerance to support 180 Hz sidebands from AM modulation.

The wide-band ultrasonic speaker is a Vifa Speaker[3]. The 25 kHz and 32 kHz transducers are driven at 7 Vpp. At least two ultrasonic signals are necessary to reproduce our experiment. We use a basic function waveform generator for the fixed 25 kHz ultrasonic transducer, and a modulation-capable signal generator for the dynamic ultrasonic source. We used a Keysight N5172B EXG X-Series RF Vector Signal Generator for the AM modulation, but many function generators also have modulation capabilities. We validated the sound waves generated by our experiment with a measurement microphone with a frequency response of 4 Hz–100 kHz[4].

[3] `https://www.avisoft.com/usg/vifa.htm`

[4] National Instruments Inc., G.R.A.S. 46BE 1/4” CCP Free-field Standard Microphone Set, `http://www.ni.com/pdf/manuals/G.R.A.S._46BE.pdf`

We used SpectrumView and Ultrasonic Analyzer to produce the Fourier transforms of the sounds we measured with the microphone in our lab. Note, microphones can also add distortion and may differ from what a human would have heard in the room. In our Fourier transforms of the IMD recorded by our measurement microphone, we noticed very clear a 7 kHz tone and a few peaks that are 180 Hz, 360 Hz, 540 Hz, 720 Hz away from 7 kHz.

4.2 Experiment with Three Ultrasonic Tones

As shown in Figure 21, we generate ultrasound at three different frequencies (25 kHz, 32 kHz, 32.18 kHz) with three devices—two 32 kHz ultrasonic transducers (for 32 kHz and 32.18 kHz) and a wide-band ultrasonic speaker (for 25 kHz). A smartphone with recording and spectrum analysis applications listen to the ultrasonic sources, which are driven by two signal generators. The spectrum, the magnified spectrum around 7 kHz, and the waterfall plot appear in Figures 21–23. The experimental findings are consistent with results of simulation, except for the 3.5 kHz and 11 kHz signals, which might be caused by imperfections of the ultrasonic speakers. Notice that the logarithmic scale spectrum resembles what we observed in the simulations, which supports the nonlinearity model.

4.3 Experiment with Modulation

Our experiments tested a couple modulation schemes, including AM and FM. The FM (Figure 25) does not appear to match well with the AP News recording, but the AM modulation does (Figure 24).

4.4 Experiments with Video Demonstrations

The following videos show our experiments in action. The white appliance is the Keysight N5172B EXG X-Series RF Vector Signal Generator for the AM modulation, and it is connected to the silver ultrasonic speaker with orange rims on the right (the ultrasonic Vifa Speaker); the grey appliance is the signal generator that drives the fixed ultrasonic transducers. Note, in the picture above, we

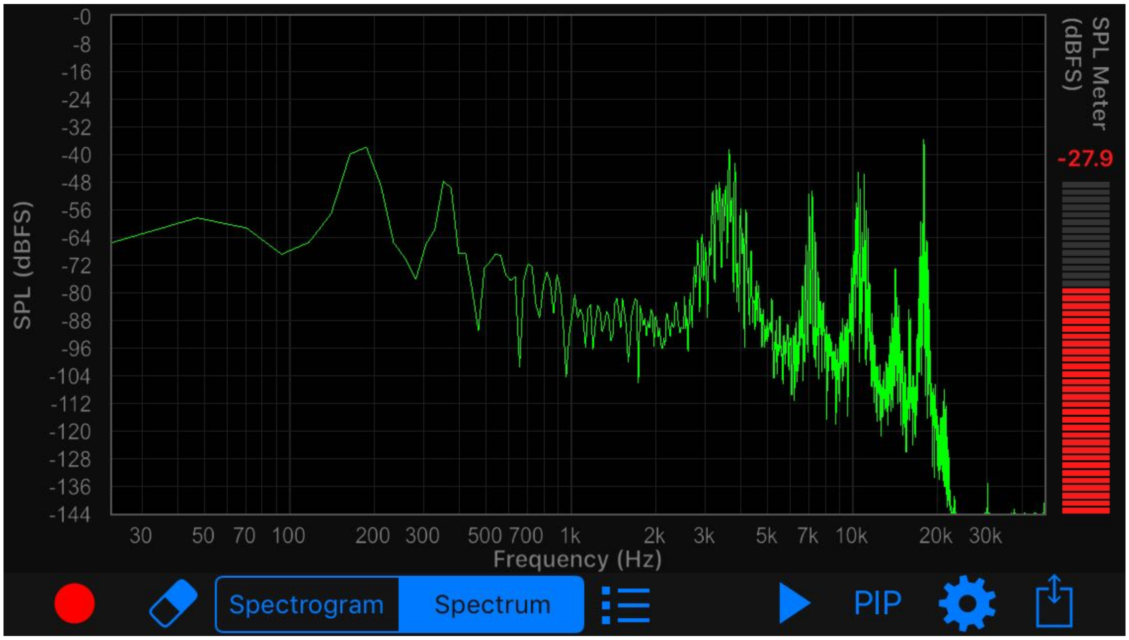

Figure 21: *Spectrum recorded during an IMD experiment playing three ultrasonic tones (25 kHz, 32 kHz, 32.18 kHz).*

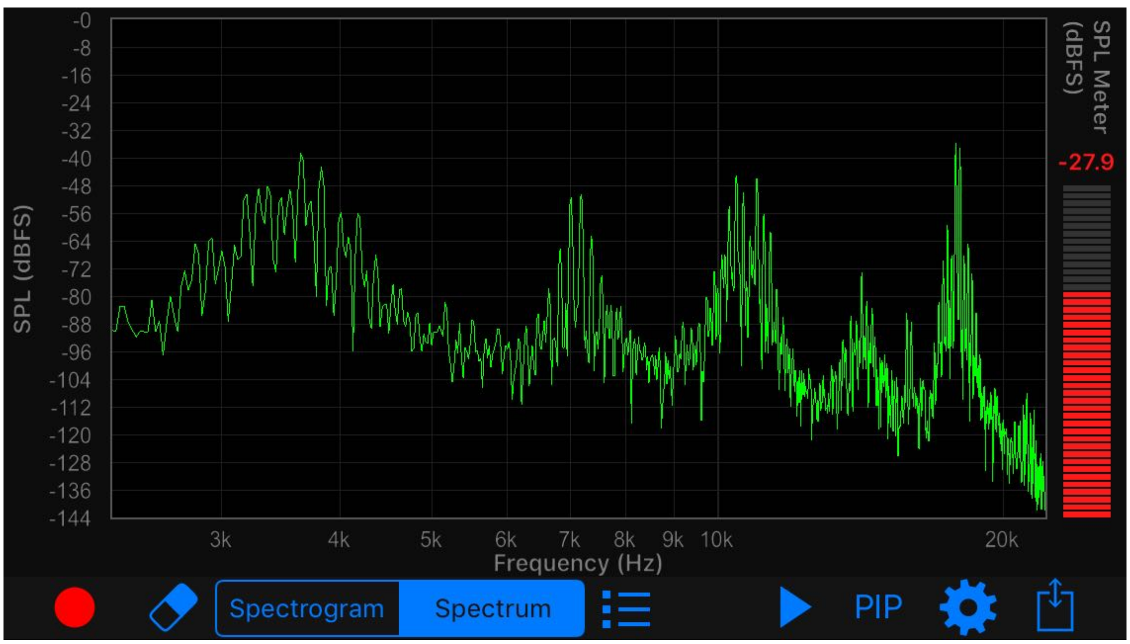

Figure 22: *Magnified spectrum of the signals near 7 kHz during an IMD experiment playing three ultrasonic tones (25 kHz, 32 kHz, 32.18 kHz)*

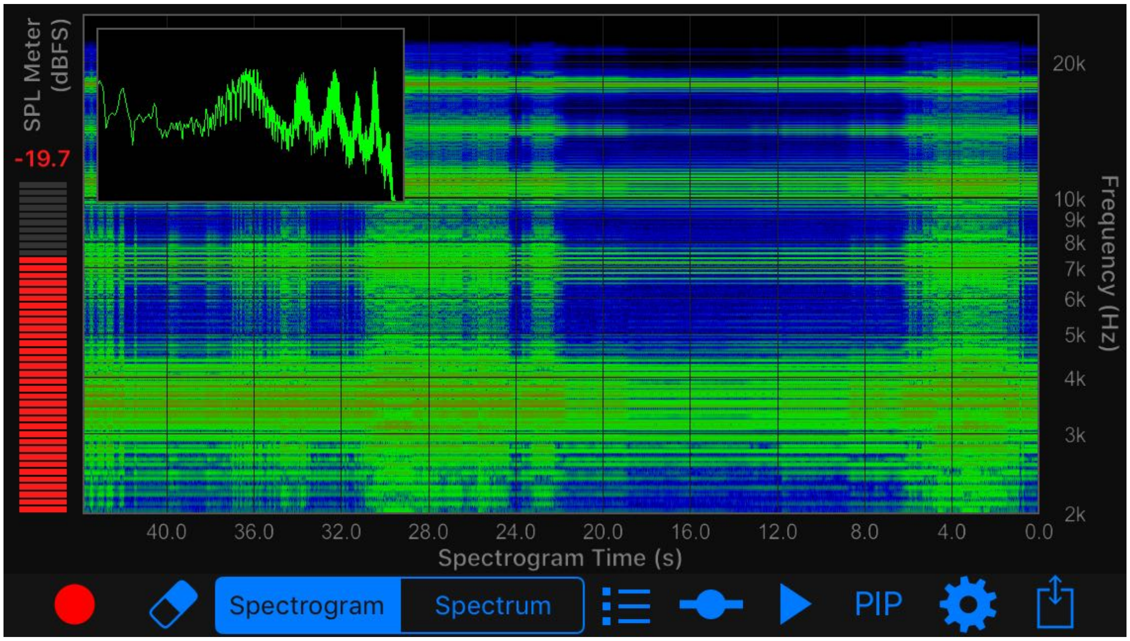

Figure 23: *Waterfall plot during an IMD experiment playing three ultrasonic tones (25 kHz, 32 kHz, 32.18 kHz).*

have two fixed ultrasonic transducers instead of one. The black smartphone in the middle serves as a spectrum analyzer.

Science of Synthesizing Audible Sounds from Ultrasonic Intermodulation Distortion. How can inaudible ultrasonic signals lead to audible byproducts? When multiple ultrasonic tones pass through a nonlinear medium such as air or a microphone, the result is intermodulation distortion[5]. In our experiment, we have two signals. One is a 180 Hz sine wave AM modulated over a 32 kHz ultrasonic carrier. The second is a simple 25 kHz ultrasonic sine wave. The smartphone displays the Fourier transform of repeated intermodulation distortion in the air and smartphone microphone circuitry. The 2nd order intermodulation distortion includes the difference between the two signals, which appears centered at 7 kHz and peppered with sidebands from the modulated 180 Hz. The higher order intermodulation distortion products create additional ripples in the spectrum at 7 kHz as well as several other frequencies. Matlab simulations predict the strong 7 kHz intermodulation distortion product, and we suspect the 4 kHz tones are the result of secondary intermodulation

[5] `https://youtu.be/wA2MZshrafk`

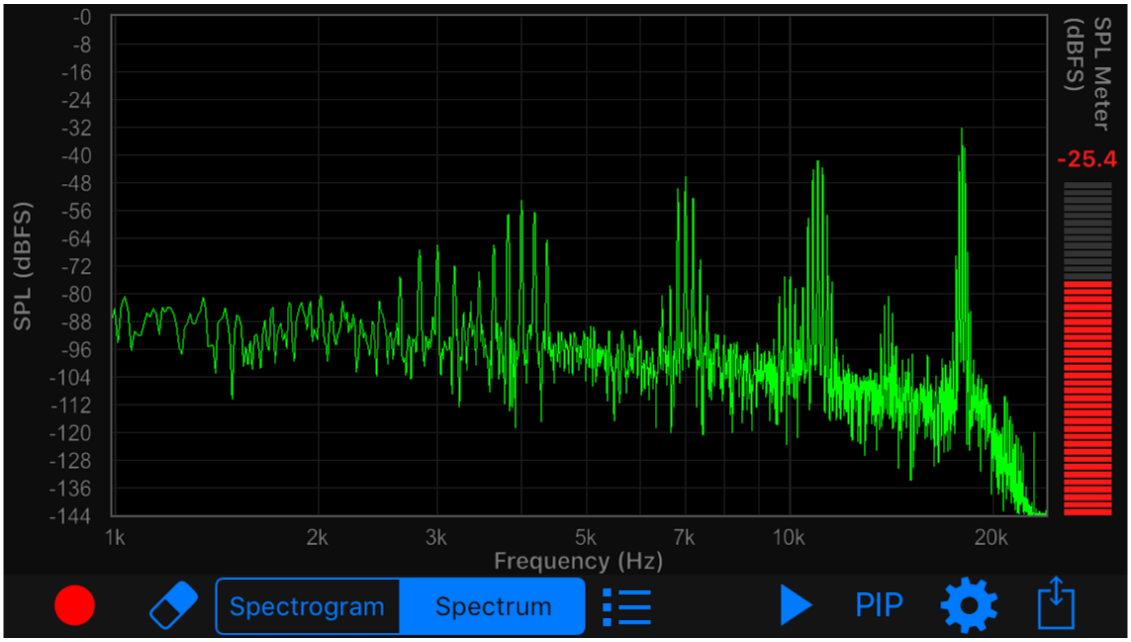

Figure 24: *Spectrum of sounds heard by a smart phone when playing 25 kHz and 180 Hz AM modulated on a 32 kHz carrer. The IMD spectrum resembles the ripples near 7 kHz in the AP news spectrum.*

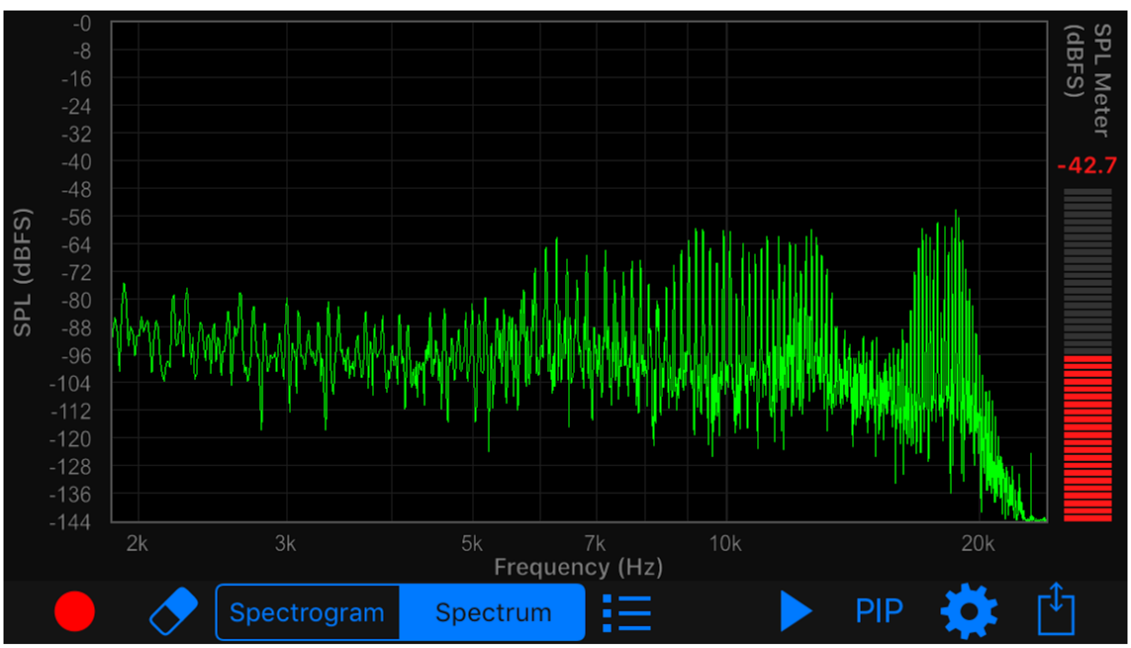

Figure 25: *Spectrum of sounds heard by a smart phone when playing 25 kHz and 180 Hz FM modulated on a 32 kHz carrer.*

distortion in the microphone.

At the beginning of the video, only the AM modulated signal (32 kHz carrier & 180 Hz sinusoidal baseband) is played through the ultrasonic Vifa Speaker, and the modulated ultrasounds cannot be heard or seen on the spectrum, which is out of the range of the spectrum plots. Once the signal generator starts to drive the fixed ultrasonic transducer to transmit a 25 kHz tone, we observe the IMD, as the spectrum analyzer shows, and can hear the high-pitched sounds.

Localized Audible Sounds Synthesized from Ultrasonic Intermodulation Distortion. Using two signal generators of low-intensity ultrasonic tones, we demonstrate synthesis of audible byproducts below 20 kHz[6]. Note, there are likely two cascading instances of intermodulation distortion: Once in the air that nearby humans can perceive, and a second time in the microphone of this smartphone. Thus, recordings of sound in Cuba are unlikely to match perfectly what humans perceived. In this experiment, our smartphone sensed a 4 kHz tone, but the student conducting the experiment could not hear a 4 kHz tone. Also note that the smartphone microphone has a frequency response that tapers off quickly after 20 kHz.

Absence of Audible Intermodulation Distortion from Single Ultrasonic Tone. Using two signal generators of ultrasonic tones, we demonstrate that the audible byproducts disappear when we disable one of the ultrasonic sources[7]. This is because at least two signals are necessary to elicit intermodulation distortion from a nonlinear medium such as air or microphone amplification circuitry.

Covertly Exfiltrating a Song with an Ultrasonic Carrier. This proof of concept shows two things: (1) how ultrasound can be used to covertly exfiltrate data (in this toy example, the audio from a memetastic song serves as a stand-in for eavedropping a conversation) and (2) how the covert channel becomes audibly overt when a second ultrasonic tone interferes. In this video[8], there are three microphones, two ultrasonic transmitters, and one audible speaker. One GRAS

[6] `https://youtu.be/ZTLjs4dbnEA`
[7] `https://youtu.be/o9jqwk83PSM`
[8] `https://youtu.be/w7_J1E5g8YQ`

ultrasonic microphone, one audible microphone on the iPhone plotting the FFT, and one audible microphone on the video recording device. The Vifa dynamic ultrasonic speaker emits the music modulated on an ultrasonic carrier. A small ultrasonic emitter sends out a single 32 kHz tone. A computer processing the ultrasonic signals from the G.R.A.S. microphone demodulates the signal and plays the resulting data, which is the song except when IMD causes corruption of the demodulation.

4.5 Discussion of Experiments

Our ultrasonic experiments create small, focused areas where one can perceive the audible sounds. Only where the ultrasonic beams cross do the sounds become apparent. Moving even a few inches from the beam can change the pitch, intensity, and sensation.

Our experiments were carried out in a lab at extremely low amplitudes to ensure the safety of the researchers.

The IMD products generated in our lab differ from the AP news recording in that we notice a set of tones at 4 kHz. IMD can happen between two signals and among more than two signals. To illustrate, we carried out experiments with multiple ultrasonic signals. While the student carrying out the experiment did hear the 7 kHz tone with his own ears, he could not hear the 4 kHz tone. We suspect that non linearities in our measurement microphone created this additional 4 kHz IMD. This observation is consistent with IMD we have found in other microphones from our previous research on ultrasonic cybersecurity [28].

5 Safety and Neurological Implications

There are two important questions that affect humans. What types of ultrasound can lead to hazardous situations or harm, and what are the neurological effects on humans?

Safety: Hazards, Hazardous Situations, Harm. We find little consensus on the risks of human exposure to air-borne ultrasound [21, 1]. Airborne ultrasonic waves on their own are not necessarily harmful, but it may become harmful at large intensity or when in direct contact exposure to a vibrating source. In direct contact exposure rather than by air, ultrasound can cause thermal injuries [1]. OSHA warns of potential harm from subharmonics of ultrasound [3], and appears to set a safety threshold in an abundance of caution. Health Canada [1] sets stricter safety requirements for the intensity of airborne ultrasound based on "plausible" risks of heating and cavitation as well as auditory and subjective effects. Canada sets a conservative 110 dB safety limit on emissions of airborne ultrasound.

According to the news [16], "The AP reported last month that some people experienced attacks or heard sounds that were narrowly confined to a room or parts of a room." Such a sensation is typical for ultrasound because ultrasound is more directional than audible sound and infrasound. Ultrasound can be focused on a certain area. Therefore, ultrasound would match the symtoms of discomfort.

Neurological Effects of Ultrasound. Researchers analyzed the effects of intense sounds on humans, but we find that the outcomes include large safety margins to make up for lack of consensus [4]. The *Handbook Human Vibration* [9] and an ISO standard [2] explore the physiological effects of low frequency vibrations and sounds. We have found little in the way of reproducible control trials for ultrasonic vibrations aside from folklore. Neurologists who examined the injured diplomats published their findings in JAMA [25], and suggest that the neurological damage is real. However, there are limitations to the retroactive study [18]—namely, causality is difficult to establish without a control trial or elimination of other null hypotheses. Our report does not itself contribute any new findings on neurological harm.

6 Alternative Explanations

While our results do not rule out other potential causes, the results do rule in the notion that ultrasound without harmful intent could have led to accidental harm to diplomats in Cuba.

We originally suspected subharmonics of ultrasound as the cause, but this hypothesis would not align well with the spectral analysis by the AP news. Rather than evenly spaced ripples in the frequency domain, we would expect to see frequencies at $1/n$ submultiples of the fundamental frequency for integers n if subharmonics were to blame.

180 Hz happens to be the high end of the fundamental frequencies of average male conversational voices. It may be coincidence that the tones are 180 Hz apart, but it could also indicate some kind of voice eavesdropping modulated over ultrasound and gone awry.

7 Related Work

The notion of using audible and inaudible sound to cause auditory and sensory illusions is not new. Our results build upon the following research.

Research from the music community used AM modulation on ultrasound to generate focused audible sound [19]. This research evolved into a company called Holosonics[9] with a product called Audio Spotlight for music, personalized sound, and museum exhibits, among other artistic applications. Companies such as the LRAD Corporation[10] produce products that deliver higher intensity sounds with military application to crowd control and long-distance hailing at sea. However, modern LRADs use audible parametric sound rather than ultrasound. Projects such as Soundlazer[11] allow the hobbyist engineer to play with ultrasonic generation of audible tones. Musicians have also used intermodulation distortion of *audible* tones to synthesize additional audible tones from nonlinearities of the inner ear [14]. Campbell even describes his realization of hearing synthesized combination tones (also known as intermodulation distortion) while listening to a movement in Sibelius's Symphony #1 [6].

Several researchers use ultrasound to fool sensors such as microphones. The BackDoor paper from Illinois [20] uses ultrasound and intermodulation distortion to jam eavesdropping microphones and watermark music played at concerts. A team from Korea uses both audible and ultrasonic tones to cause malfunctions in flight stability control of drones by acoustic interference at the resonant frequency of MEMS gyroscopes [22].

[9] `https://www.holosonics.com/`
[10] `https://www.lradx.com/`
[11] `http://www.soundlazer.com/`

In our past research, we use audible and ultrasonic tones to test the cybersecurity of computer systems. The DolphinAttack paper [28] uses ultrasound and intermodulation distortion to inject inaudible, fake voice commands into speech recognition systems including Siri, Google Now, Samsung S Voice, Huawei HiVoice, Cortana, Alexa, and the navigation system of an Audi automobile. Researchers from Princeton [23] investigate inaudible voice commands from ultrasound on Android phones and Amazon Echo. The Walnut paper [26] exploits nonlinear amplifiers, permissive analog filters, and signal aliasing to adulterate the output of MEMS accelerometers with sound waves at the resonant frequency of the sensor found in applications such as Fitbits, airbags, and smartphones. The sensors effectively serve as unintentional demodulators of the sound. Our upcoming Blue Note [5] paper analyzes the physics of why hard drives and operating systems get corrupted or spontaneously reboot when subjected to certain ultrasonic tones or by clicking on a link to a web site that plays maliciously crafted sound through the victim computer's mechanically coupled speakers.

We have urged more attention to the physics of cybersecurity [7], and the events in Cuba provide more evidence of the need to understand the causal relationships between physics and cybersecurity.

8 Unresolved Questions

Our report only rules in ultrasound and intermodulation distortion as a cause. It does not eliminate other hypotheses. In particular, several mysteries remain:

- How could ultrasound penetrate walls into homes and offices? Could an emitter be outside the premises or planted inside? Was it primarily air-borne, or did it originate as contact vibration?
- At what level of intensity could IMD products cause harm to humans? We know of no non-trivial lower bounds. Based on our reading of various safety documents, we believe most countries set conservative thresholds for airborne ultrasound from an abundance of caution and to compensate for uncertainty. While there are anecdotes and folklore for harm from

airborne ultrasound, we have found no primary sources that confirm this aside from stories about extremely intense sounds above 155 dB.

- What about standoff distance? Our report does not investigate distance. We do not have a facility to safely test high intensity ultrasound, but might look into it in the future if can borrow an airport runway.
- Could audible tones be a symptom or cause? Without a control study, it would be difficult to distinguish a cause from a symptom. It's possible that the audible sensations are byproducts from contact vibration or some other ultrasonic source.

9 Conclusion

Two inaudible ultrasonic signals mixing in a nonlinear medium could easily lead to an audible intermodulation distortion product. Although little is known about how audible sound waves can cause neurological damage rather than merely be correlated with neurological damage, the safety community has studied how certain audible sounds can cause pain and hearing damage. Thus, ultrasonic intermodulation distortion could produce harmful, audible byproducts. The safety warnings on audible frequencies and intensities would apply to these byproducts.

While our experiments do not eliminate the possibility of malicious intent to harm diplomats, our experiments do show that whoever caused the sensations may have had no intent for harm. The emitter source remains an open question, but could range from covert ultrasonic exfiltration of modulated data to ultrasonic jammers of eavesdropping devices or perhaps just ultrasonic pest repellents. It's also possible that someone was trying to covertly deliver data into a localized space using ultrasound to say, activate a sensor or other hidden device. Our experiments show that tones modulated on an ultrasonic carrier by one or more parties could have collided invisibly to produce audible byproducts. These audible byproducts can exist at frequencies known to cause annoyance and pain. Other theories include solid vibration (e.g., unwittingly standing on a covert transmitter) at ultrasonic frequencies for prolonged periods—leading to bodily harm. In such a case, audible intermodulation distortion could represent a harmless side effect rather than the cause of harm. Although our tests focus on frequencies rather than amplitudes or distances, we believe that high amplitude ultrasonic signals could easily produce high amplitude audible signals as unintentional byproducts capable of harm to hearing.

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The link between health complaints and wind turbines: support for the nocebo expectations hypothesis

Fiona Crichton[1]*, Simon Chapman[2], Tim Cundy[3] and Keith J. Petrie[1]

[1] Department of Psychological Medicine, University of Auckland, Auckland, New Zealand
[2] School of Public Health, University of Sydney, Sydney, NSW, Australia
[3] Department of Medicine, University of Auckland, Auckland, New Zealand

Edited by:
Loren Knopper, Intrinsik Environmental Sciences Inc., Canada

Reviewed by:
Robert G. Berger, Intrinsik Environmental Sciences Inc., Canada
James Rubin, King's College London, UK

***Correspondence:**
Fiona Crichton, Department of Psychological Medicine, Faculty of Medical and Health Sciences, University of Auckland, Private Bag 92019, Auckland, New Zealand
e-mail: f.crichton@auckland.ac.nz

The worldwide expansion of wind energy has met with opposition based on concerns that the infrasound generated by wind turbines causes health problems in nearby residents. In this paper, we argue that health complaints are more likely to be explained by the nocebo response, whereby adverse effects are generated by negative expectations. When individuals expect a feature of their environment or medical treatment to produce illness or symptoms, then this may start a process where the individual looks for symptoms or signs of illness to confirm these negative expectations. As physical symptoms are common in healthy people, there is considerable scope for people to match symptoms with their negative expectations. To support this hypothesis, we draw an evidence from experimental studies that show that, during exposure to wind farm sound, expectations about infrasound can influence symptoms and mood in both positive and negative directions, depending on how expectations are framed. We also consider epidemiological work showing that health complaints have primarily been located in areas that have received the most negative publicity about the harmful effects of turbines. The social aspect of symptom complaints in a community is also discussed as an important process in increasing symptom reports. Media stories, publicity, or social discourse about the reported health effects of wind turbines are likely to trigger reports of similar symptoms, regardless of exposure. Finally, we present evidence to show that the same pattern of health complaints following negative information about wind turbines has also been found in other types of environmental concerns and scares.

Keywords: wind farms, infrasound, nocebo effect, psychological expectations, health scares, symptom reporting, environmental risks, media warnings

INTRODUCTION

In recent years, challenges to new wind farm developments have been mounted on the basis that exposure to sound, and particularly infrasound, generated by wind turbines poses a health risk (1). Unfortunately, addressing concerns about health effects has been complicated by a lack of clarity about what might be causing the symptoms reported. Perceived adverse health effects said to be experienced by people living near wind turbines include symptoms such as sleep disturbance, headache, earache, tinnitus, nausea, dizziness, heart palpitations, vibrations within the body, aching joints, blurred vision, upset stomach, and short-term memory problems (2). In this article, we explore factors that might explain symptom reporting attributed to wind farms and put forward the case for the nocebo expectations hypothesis; that symptom reporting can be explained by negative expectations, rather than any pathophysiological link between symptoms and wind farm sound. Research consistently indicates that the expectation of adverse health effects can itself produce negative health outcomes, which is a phenomenon known as the nocebo effect (3). Negative expectations generating nocebo responses have been shown to have a powerful influence on health outcomes in clinical populations (4), and reported symptom experiences in community samples (5).

THE LINK BETWEEN WIND FARM SOUND AND HEALTH COMPLAINTS

When investigating the cause of symptom reporting attributed to any purported environmental hazard, it is axiomatic that the existence of a biological basis for symptomatic experiences is thoroughly explored, so that an organic cause of symptoms is not erroneously discounted (6). Given that symptom reporting has been attributed to wind farm sound (2), it is necessary to consider the evidence for any direct relationship between exposure to such sound and symptom reporting. Given reductions in mechanical noise, as a result of refinements to wind turbine design, aerodynamic sound is now the dominant source of noise from modern wind farms (7). This aerodynamic noise, which is generated as a result of the flow of air past the turbine blades, is present across a range of frequencies, from the audible to sub-audible infrasound (8).

At this time, studies have not found a direct causal link between living in the vicinity of wind farms, audible wind farm sound exposure, and physiological health effects (1). Audible sound levels, assessed at the nearest residence, have been consistently found to fall within accepted health and safety limits for ambient background noise, and evidence does not support a direct link between such sound exposure and symptom reporting (9).

To elaborate further, although a small proportion of people report being annoyed by wind farm sound, particularly by detectable fluctuations of sound in the mid-frequency range (500–1000 Hz), the evidence does not indicate that exposure to such sound is directly causing adverse physiological effects in those living in the vicinity of wind farms (8). In addition, despite concerns that audible low frequency noise (20–200 Hz) produced by wind turbines is triggering symptomatic experiences, this is not supported by the scientific evidence (10).

Further, the evidence does not substantiate conjecture that exposure to sub-audible wind farm generated infrasound (sound below 20 Hz) is responsible for health complaints. It is important to note that exposure to infrasound is an everyday experience. Infrasound is constantly present in the external environment, caused by phenomena such as weather variations, air turbulence, ocean waves, traffic, and other machinery (11). Notably, the body and vestibular systems have evolved to prevent disturbance from infrasound generated from internal processes, such as respiration and heart rate, which is produced at higher levels than infrasound generated by wind farms (12). While sound in the infrasonic range may become audible at sufficiently high pressure levels, infrasound produced by wind turbines is below the threshold of human perception (11, 13), and research does not support the existence of adverse health effects of exposure to infrasound at sub-audible levels (14). Importantly, a recent investigation found the contribution of wind turbines to measured infrasound levels at residential locations near wind farms was insignificant in comparison with the background level of infrasound in the environment (15). Given consistent evidence that infrasound produced by wind turbines does not exceed typical levels of infrasound found in everyday urban or rural environments, health impacts of infrasound produced by wind turbines are not indicated (12, 16).

As the evidence does not support a direct link between audible or sub-audible sound generated by wind turbines and reported symptomatic experiences by people living in the vicinity of wind farms, it is apparent that factors beyond exposure to wind turbine sound are implicated in symptom reporting.

PERCEPTION OF HEALTH RISK AND EXPECTATIONS

There is accruing evidence that some people facing the prospect of a new wind farm near their residence, or currently living within the vicinity of a wind farm, are genuinely fearful of the potential health effects of operating wind turbines (1). This has relevance as evidence shows a relationship between assessment of health risk and symptom reporting, which does not depend upon whether a health risk is genuine (17). This is seen in community examples where there has been an error about exposure to a perceived toxic agent. In one such case, symptom complaints attributed to exposure to electromagnetic radiation from a mobile phone tower occurred when the tower itself was not yet active (18).

In fact, extreme increases in symptom reports, in instances of both genuine and perceived toxic exposure to harmful agents, have been repeatedly shown in community settings (19) with strength of environmental concern being a critical factor in predicting the occurrence of symptom complaints (20). This was highlighted in a study in which participants, from 10 villages in Germany, had their sleep monitored over 12 nights during which they were exposed to sham signals and electromagnetic field signals from an experimental base station (21). There was no evidence for short-term physiological effects of electromagnetic fields emitted by mobile phone base stations on sleep quality, but findings demonstrated a negative influence on objective and subjective sleep quality in subjects who were concerned that proximity to mobile phone base stations might negatively affect health.

Evidence shows that health-related worries about perceived environmental hazards inform negative expectations, which in turn draw attention to body processes and shape how individuals decipher symptoms [e.g., Ref. (22)]. Negative expectations translate into symptomatic experiences, because focused attention to the body has the tendency to draw awareness to common sensations that might otherwise go unnoticed (23). Further, increased anxiety itself causes a rise in physiological activity giving rise to symptoms such as dry mouth and rapid heart-beat (23). Evidence suggests people may misinterpret symptoms of hypervigilance and anxiety as a sign of illness, particularly if symptoms experienced are consistent with concerns about health (24).

Recently, there has been a noticeable rise in the number of people expressing concern about health effects presented by the sound generated by wind farms, and fears about health risk have emerged as a key predictor of opposition to wind farm development (25, 26). Such fears are more prominent in countries where wind farms are relative new comers on the landscape, which aligns with consistent evidence of associations between the introduction of new technologies, community concern about related health risks, and symptom reporting (27, 28).

MATTER OF EXPECTATION

While the operation of modern commercial wind farms commenced more than 20 years ago in several nations, widespread claims that exposure to wind farm sound produces adverse, often acute and immediate, symptomatic experiences, are much more recent (29). This change is reflected in the shifting focus of community opposition to wind farms over time. Historically, community opposition to wind farms has centered on concerns about depreciation of property values, problems with esthetic integration on the landscape, and apprehension about the intrusiveness of noise produced by wind turbines (30, 31). However, in recent years, concern about the adverse health risk of exposure to wind turbine sound has repeatedly emerged as a new focal point of community opposition to wind farms, indicating a change in the way in which wind farms are now perceived (1).

Such concern, as well as a dramatic amplification of symptom reports (29), coincided with the promotion in 2009 of the self-published book *Wind Turbine Syndrome-A Natural Experiment* (2), also available and summarized on the internet. The book portrays infrasound produced by wind turbines as a threat to health, and explicitly sets out the physical symptoms and health effects to be expected by those living in proximity to a wind farm. Given that wind farms simultaneously generate infrasound and audible sound, negative health information about infrasound is likely to influence the perception of wind farm sound in its entirety. Further, although the narrative of the book emphasizes the perniciousness of the sub-audible components of wind farm sound, it also sets out health concerns about audible sound, particularly low frequency audible wind farm sound. Thus, health concerns triggered by the type of information contained in the book are likely to inform negative expectations extending to both the audible and sub-audible components of wind farm sound exposure.

The concurrence of the publication of *Wind Turbine Syndrome-A Natural Experiment* and an increase in symptom reporting attributed to wind farms (29) supports the argument that symptoms are more likely due to negative expectations triggered by health information, rather than being caused by pathogenic exposure to wind farm sound. This is exemplified in a study assessing historical complaints, in relation to 51 Australian wind farms operating from 1993 to 2012 (29). Findings illustrated that, prior to 2009, health and noise complaints were rare, despite small and large wind farms having operated in Australia for many years. The study found that 90% of complainants made their first complaint post 2009, after anti-wind farm campaigners disseminated information about the purported health effects of wind farms. Further, the majority of complaints were confined to the six wind farms targeted by anti-wind farm campaigners, indicating complainants had accessed negative health information (29).

Additional support for the involvement of negative expectations, in relation to the increase in symptom reporting seen since 2009, is also provided by recent field research demonstrating that people higher in negative-oriented personality traits are more likely to report higher levels of perceived noise (unrelated to actual noise levels) and more non-specific physical symptoms around wind farms (32). Experimental research demonstrates that individuals with higher levels of negative affect are more susceptible to the influence of expectations about health effects created by suggestion and more likely to report expectation consistent symptoms (33).

The ascription of a disease label "Wind Turbine Syndrome" is a powerful way to create health concerns and set expectations. Where individuals adopt disease labels to reflect symptomatic experiences attributed to environmental causes they are more likely to be concerned about the environmental health risk posed, and less likely to be reassured by scientific investigation if it indicates there is no link between the perceived environmental hazard and symptoms (34). The use of an illness label "Wind Turbine Syndrome" (2), along with a widely publicized and explicated list of syndrome symptoms, not only creates the impression that there is a risk that those living near wind turbines will develop a recognized medical condition, but also creates a comprehensive idea of expected symptoms. Simply reading about symptoms of an illness can prompt self-detection of disease specific symptoms, a phenomenon seen in medical student disease. Here, medical students, in the course of learning about an illness, start to experience symptoms indicative of the disease studied (35, 36). The process of learning about an illness appears to generate a cognitive representation of the illness, or mental schema, which guides the way in which internal sensory information is attended to, so that symptoms or sensations that align with the schema are noticed and reported. Symptoms that are inconsistent with the schematic representation of the relevant illness are likely to be overlooked or discounted (37).

Thus, negative expectations operate as a blueprint or heuristic for the type of symptoms attended to and reported. In a clinical research setting, a substantial number of patients, randomized to the placebo arms of placebo controlled drug trials, experience and report symptoms reflective of the side effects of active treatment [e.g., Ref. (38)]. In an experimental study, participants inhaling a benign substance, described to them as a "suspected environmental toxin" known to cause headache, nausea, itchy skin, and drowsiness, reported increases in symptoms, particularly in relation to symptoms they had been told they might expect to experience (39).

Therefore, merely being aware of the type of symptoms that have been attributed to wind turbines is likely to trigger an expectancy directed cognitive body search, whereby the body is selectively monitored for sensations and symptoms consistent with ideas about the physiological effects of exposure to wind farms. During this process, individuals will be inclined to notice common symptoms, which align with expectations and to interpret ambiguous sensations in accordance with such beliefs (40). This was demonstrated in a double-blind provocation study, where participants who watched material from the internet suggesting that infrasound produced by wind farms generated symptoms, reported significant increases from pre-exposure assessment, in the number and intensity of symptoms experienced during exposure to both infrasound and sham infrasound (41). Importantly, elevations in symptom reporting, during exposure periods, coincided with information about the precise symptom profile, said to be related to infrasound exposure. During both exposure periods, participants reported more symptoms characterized as typical symptoms of infrasound exposure, than symptoms differentiated as atypical symptoms of exposure to infrasound. Results suggested that expectations formed by accessing negative health information about wind farm sound could be providing a pathway for symptom reporting in community settings.

EXPECTATIONS AND MISATTRIBUTION

It is important to note that many of the symptoms said to arise from exposure to wind farms, such as headache, fatigue, concentration difficulties, insomnia, gastrointestinal problems, and musculoskeletal pain, are commonly experienced by healthy individuals (23). If people are worried about the health effects of an environmental agent and form symptom expectations, they are also more likely to notice and misattribute their current symptomatic experience to that environmental agent. This can occur even when symptoms are more consistent with everyday experiences and may, under different circumstances, be explained as just part and parcel of normal life (22). Given that the symptoms said to be associated with wind turbines, such as tinnitus, sleep problems, and headache, are extremely common in the general community (42–44), many hearing about a putative connection with wind turbine exposure may be persuaded that health problems they experience can be attributed to this exposure. An analysis of symptom reporting by people living in the vicinity of wind turbines in Canada indicated that the prevalence of reported symptoms was consistent with symptom prevalence in the general population, suggesting that people are likely to be misattributing their ordinary experience of common symptoms to wind turbines, rather than becoming more symptomatic (45).

Many of the symptoms associated with wind turbines, such as dizziness and heart palpitations, are also stress-related concomitants of autonomic arousal associated with anxiety and distress (46). Further, evidence indicates a bidirectional relationship between anxiety and insomnia (47), so that people who are anxious about the health effects of wind farms may experience sleep difficulties because of this anxiety, and sleep difficulties may, in turn, exacerbate the experience of physiological symptoms of anxiety. These symptoms may then be misattributed to wind farm sound, if there is an expectation that wind farm sound poses a health risk.

Evidence also indicates that fears associated with beliefs that innocuous stimuli have dangerous health consequences, engenders associations between such stimuli and stress-related symptoms, so that exposure to such stimuli may become a cue for symptom expression (48). Therefore, detecting wind turbine noise may facilitate symptom expression because, for those concerned about the health effects of wind turbines, hearing the noise signifies exposure to a perceived environmental hazard. Such an interpretation would provoke anxiety, resulting in heightened physiological arousal and stress-related symptoms.

Interestingly, evidence suggests that individuals are much less likely to be annoyed by wind turbine noise if they unable to see wind turbines from their dwelling, even if the sound itself is at a relatively high level (49). Where individuals are worried about the health effects of wind turbines, the visibility of wind turbines from a residence is likely to be a particularly concrete reminder of their concern, thus perpetuating anxiety and related physiological arousal. Therefore, both audibility of sound and visibility of a wind turbine may act as situational cues for symptom expression, triggering stress-related symptoms, thereby reinforcing health concerns (48).

Concerns about a perceived environmental hazard and corresponding negative expectations can also lead to misattribution of current illness, so that illnesses are viewed as a reaction to environmental exposure rather than the result of aging or other disease processes. Over the past 50 years, an increasing concern about the environment appears to have led to heightened sensitivities to environmental change, which have also impacted on the way people perceive illness and disease (17). Individuals are more inclined than previous generations to view ill health as a by-product of a toxic environment, and to worry about the enduring health effects of environmental changes. The propensity to look for external environmental causes for ill health is illustrated by research indicating a tendency among cancer survivors of the 10 most common cancers to believe environmental factors play a much more significant role in carcinogenesis than scientific evidence warrants (50). Therefore, an environmental change, particularly involving the use of an emerging technology, is likely to be regarded with suspicion and trigger expectations impacting on the way individuals interpret their own symptomatic experiences. Diseases such as diabetes, skin cancer, and stroke, with much more established etiology, have instead been ascribed to wind farms indicating a process of misattribution (51).

MEDIA HEALTH WARNINGS AND EXPECTATIONS

A recent study has demonstrated that the upsurge in noise and health complaints seen in Australia since 2009 has arisen primarily in localities where there has been targeted publicity about the alleged harmful impacts of wind farms (29). Two entire Australian states with wind farms, but no history of anti-wind farm advocacy, had no reported instances of health or noise complaints. Findings are consistent with research indicating that media warnings about potential harm from environmental factors may create health concerns prompting symptom reporting, even in the absence of objective health risk (48). Merely watching a television report about the supposed adverse effects of Wifi has been shown to elevate concern about the health effects of electromagnetic fields and increase the likelihood of experiencing symptoms following exposure to a sham Wifi signal (52).

In the case of wind farms, recent media stories have been shown to contain fright factors likely to trigger fear, concern, and anxiety about the health risk posed by wind turbines (53). Assertions about the adverse impacts of wind farm sound have been widely disseminated by the media, particularly via anti-wind farm internet websites, and have led to misconceptions about infrasound generated by wind turbines and a conviction in some that wind farms cause a myriad of health complaints (12) Conjecture about the adverse health effects of wind farms is a consistent theme in public discourse about wind turbines found in media reports embodied in headlines such as "*Wind turbines cause heart problems, headaches and nausea...*" (54); "*Coming to a house, farm, or school near you? Wind Turbine Syndrome...*" (55); and television news items such as "*Wind Turbines cause health problems, residents say*" (56). Further, misleading reports about the impact of living in the vicinity of wind farms, such as inaccurate accounts of home abandonment and emotive references to wind farm refugees, is also liable to create disquiet (57).

It has been verified in a recent double-blind provocation study that the kind of information disseminated in the case of wind farms elevates health concerns and creates corresponding negative expectations, which result in symptomatic experiences. Participants viewing a DVD, containing extracts from the internet outlining the alleged health effects of infrasound generated by wind turbines, reported increased concern about the health effects of sound produced by wind farms, which was associated with amplification of symptom reporting during both genuine and sham exposure to infrasound (41). Results showed negative expectations may be created by media portrayal of alleged health risks posed by the sound created by wind turbines, which could explain symptom reporting around wind farms.

The profound effect of the media narrative on the experience of wind farm sound was confirmed in a follow-up study in which subjective health was influenced in either positive or negative directions, depending on how the sound was portrayed. In keeping with previous findings, participants with negative expectations, formed from media warnings about infrasound, reported increased symptoms and deterioration in mood during simultaneous exposure to infrasound and audible wind farm sound (58). In contrast, participants delivered positive expectations derived from information extracted from the internet about the alleged therapeutic effects of infrasound, experienced an improvement in symptomatic experiences and mood. Findings demonstrated the malleability of symptomatic responses and the power of information disseminated through the media to create expectations, which determine how wind farm sound is experienced. It was particularly telling that positive expectations about infrasound triggered a placebo response in participants listening to audible wind farm sound, while being exposed to infrasound. This highlights that exposure to audible wind farm sound can be a pleasurable experience, if the narrative about the sound is depicted positively. The study provides encouraging indications that if information disseminated about wind farm sound is framed in more neutral or benign ways, then reported symptoms or negative health effects can be ameliorated.

EXPECTATIONS CREATED BY SOCIAL INTERACTIONS

It is important to bear in mind that the experience of symptoms attributed to wind turbines occurs in community settings, and in a social context where there are a range of opinions, concerns, and pressure group activity about the construction of wind farms and about possible health risks associated with them (1, 30). Evidence has shown residents' fears about the health effects of wind turbines are increasingly becoming the focal point of community public consultation meetings, formed as part of resource consent and environmental assessment processes that relate to wind farms (1). Expectations can be learned from such social interactions (59), and may also be created and reinforced by observation and modeling (Faasse et al. under review). The potential effect of observation on symptom experience is indicated in an experimental study demonstrating that one-third of healthy controls, when exposed to images of other people in pain, reported pain in the same location as the observed pain (60). Further, in an experimental study in which participants inhaled an inert substance portrayed as a possible environmental toxin, seeing someone exhibiting expected symptoms increased participant reports of those specific symptoms, illustrating the phenomenon of contagion by observation, seen in mass psychogenic illness (61).

There are various avenues for observation and modeling of symptoms within communities where wind farms are established. Neighbors and members of the wider community may be exhibiting and talking about their symptomatic experiences, which they attribute to wind farms. Television reports about the health effects of wind turbines have also incorporated interviews with symptomatic people, describing their experiences in detail, providing another medium by which symptoms may be modeled [e.g., Ref. (56)]. These interviews can usually be accessed on the internet, so people researching the effects of wind farms can observe modeled behavior with ease.

There are also indications that, where symptoms are attributed to wind turbines, health problems are reported by everyone within the affected household, including children [e.g., Ref. (2)]. This suggests that familial modeling may play a role in symptom reporting, particularly in relation to affected children. Parental pain and symptom modeling is implicated in the development of unexplained pain and somatic complaints in pediatric populations (62, 63).

ANNOYANCE AND EXPECTATIONS

It seems apparent that elevated concern about the health effects of living in the vicinity of wind farms, and the related formation of negative expectations, is also exacerbating reported annoyance with wind farm sound. There is much variability between studies in relation to the extent of reported wind farm noise annoyance indicating that contextual matters are influencing annoyance reactions. Related studies undertaken in Sweden and the Netherlands have indicated that approximately 10–20% of residents living in proximity to wind farms find wind turbine noise annoying, and 6% of residents find wind turbine noise very annoying, at 35–40 dB exposure (7, 49, 64). However, another study conducted in New Zealand reported that 59% of respondents living within 2 km of a wind farm experienced noise annoyance (65). The New Zealand study was undertaken at a time when there had been adverse publicity about expected noise and health effects of living in the vicinity of the wind farm in question, including a story that aired on free to air television (66). Understanding the factors that contribute to annoyance is important because, although noise annoyance is not in itself a disease or health state, annoyance is related to distress, which can lead to the experience of stress-related symptoms (9, 67).

Being annoyed by noise is related to a range of personal and situational variables, beyond the acoustic characteristics of noise (68, 69), and psychosocial factors account for more variation in individual annoyance, than objective measures of noise level (70). Experimental work indicates that not being aware of the source of sound is associated with reduced noise annoyance in people exposed to wind farm sound, further confirming that the context of sound exposure has more relevance for annoyance assessment, than the acoustic properties of wind farm sound (71). Importantly, a strong relationship has been found between concern about the negative health effects of noise and noise annoyance (72). The evidence also shows that wind turbine noise annoyance is more strongly related to other negative attitudes about wind turbines, particularly the visual impact of wind turbines on the land scape, than to sound level (7, 49). Thus, rhetoric that creates health concerns about wind turbine sound, and presents a negative view of wind farms, is likely to influence not just symptom reporting and distress, but reported noise annoyance.

There is compelling evidence that creating a positive context for the experience of wind farm sound, has a correspondingly positive impact on reported annoyance. A field study conducted in The Netherlands indicated that respondents who benefited economically from wind turbines, by either full or partial turbine ownership or by receipt of other economic benefits, such as a yearly income, were less annoyed by wind turbine noise than other respondents, despite exposure to higher sound levels (49). Notably, there were no differences in either likelihood to notice sound, or subjective noise sensitivity between those who did or did not derive economic benefit. However, there were attitudinal differences. Respondents who benefited economically were less negative both about wind turbines in general, and about the visual impact of wind turbines on the landscape. Results suggest that experiencing wind farm sound in a positive context decreases the likelihood of forming negative views of wind turbines associated with annoyance. This provides promising indications that changing the narrative around wind farms, so that worried residents become less concerned about their proximity to wind farms and adopt more positive expectations and attitudes, might not only alleviate symptom reporting but also reduce noise annoyance.

PATTERNS OF HEALTH COMPLAINTS SEEN IN OTHER INSTANCES OF PERCEIVED TOXIC EXPOSURE

It is relevant to note that symptom reporting, in response to perceived exposure to a toxic agent when no plausible health threat is posed, has been seen throughout history (17). Francis Bacon (1561–1626) noted "*infections…if you fear them, you call then upon you*" (73). In one pertinent example, a dramatic elevation in reported symptoms in a community setting in Memphis followed a health scare fueled by media messages that the town was located in close proximity to an old toxic waste dump (74). While a comprehensive examination of soil toxicity revealed no hazard was presented, health fears did not abate until it became apparent authorities were mistaken as to the locality of the dump, which had actually been situated many miles from the town (19). Although symptom reporting then subsided, some residents continued to insist they experienced symptoms from the phantom dump site.

Further, the advent of new technologies has consistently been associated with the development of subjective illness complaints, involving a constellation of symptoms, akin to those attributed to wind farms (28, 75). For instance, in 1889, following the increasing use of the telephone, The British Medical Journal cautioned about the emergence of "*telephone tinnitus*" in respect of which "*the patients suffered from nervous excitability, with buzzing noises in the ear, giddiness, and neuralgic pains*" (76). With striking parallels, almost a century later, the experience of a range of non-specific symptoms such as headache, fatigue, tinnitus, and concentration problems have been attributed by some individuals to exposure to electromagnetic fields via mobile telephones (77). This occurs despite the fact there is no generally accepted causal bio-electromagnetic mechanism, by which such symptoms would be triggered (78). Given that provocation studies have repeatedly shown that sham electromagnetic exposure is sufficient to activate symptoms in individuals who believe they are sensitive to electromagnetic fields, the evidence suggests the involvement of nocebo responses; that it is anxiety about exposure and related negative expectations, which are triggering symptomatic experiences (52).

CONCLUSION

An analysis of the evidence concerning symptom reporting attributed to sound produced by wind farms supports the nocebo expectation hypothesis; that health complaints can be explained by the influence of negative expectations. It is apparent that symptom reporting coincided with an increase in health concern about wind farms promoted by a book and internet sites focused on highlighting the purported heath dangers posed by sound, particularly infrasound produced by wind turbines. Such information, which has been further circulated though social discourse and media reporting, is liable to trigger health concerns and related symptoms of anxiety, while also creating a blueprint for what symptoms can be expected – expectations, which, in turn, are likely to guide the type of symptoms noticed and reported. This is supported by epidemiological evidence that increased symptom reporting has occurred in locations where there has been targeted dissemination of negative health information about wind farms, indicating that exposure to such information is shaping symptomatic experiences. Experimental work also suggests that it is expectation rather than wind farm sound exposure that is responsible for symptom complaints.

Symptom reporting is also consistent with patterns of health complaints seen in other environmental health scares involving benign exposure, and which often follow the introduction of new technologies. Importantly, indications that negative expectations are implicated in symptomatic experiences ascribed to wind farms aligns with evidence that instances of symptom reporting attributed to perceived environmental hazards and exposure to modern technologies have been triggered by nocebo responses.

Understanding the underlying cause of health concerns and symptom complaints, which have arisen in communities in which wind farms have been proposed and developed, is critical if such concerns are to be addressed, and symptom reporting alleviated. Given indications of the determinative role of negative expectations in creating and maintaining symptom reporting, successful strategies to address health complaints are likely to involve changing the narrative about wind farms, to create more positive expectations.

AUTHOR CONTRIBUTIONS

All authors contributed to the conceptualization, writing, and editing of this manuscript.

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New Insights into the Placebo and Nocebo Responses

Paul Enck,[1,*] Fabrizio Benedetti,[2] and Manfred Schedlowski[3]
[1]Department of Internal Medicine VI: Psychosomatic Medicine and Psychotherapy, University Hospital, 72076 Tübingen, Germany
[2]Department of Neuroscience, University of Turin Medical School, and National Institute of Neuroscience, 10125 Turin, Italy
[3]Institute of Medical Psychology and Behavioral Immunobiology, Medical Faculty, University of Duisburg-Essen, 47048 Duisburg-Essen, Germany
*Correspondence: paul.enck@uni-tuebingen.de
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In modern medicine, the placebo response or placebo effect has often been regarded as a nuisance in basic research and particularly in clinical research. The latest scientific evidence has demonstrated, however, that the placebo effect and the nocebo effect, the negative effects of placebo, stem from highly active processes in the brain that are mediated by psychological mechanisms such as expectation and conditioning. These processes have been described in some detail for many diseases and treatments, and we now know that they can represent both strength and vulnerability in the course of a disease as well as in the response to a therapy. However, recent research and current knowledge raise several issues that we shall address in this review. We will discuss current neurobiological models like expectation-induced activation of the brain reward circuitry, Pavlovian conditioning, and anxiety mechanisms of the nocebo response. We will further explore the nature of the placebo responses in clinical trials and address major questions for future research such as the relationship between expectations and conditioning in placebo effects, the existence of a consistent brain network for all placebo effects, the role of gender in placebo effects, and the impact of getting drug-like effects without drugs.

Introduction

Recent experimental work clearly demonstrates that a better understanding of the neurobiology and psychology of the placebo and nocebo responses is of great importance, as it might have profound implications for basic and clinical research and clinical practice. In basic research, we can learn more about how psychological processes affect CNS neurochemistry and how these alterations subsequently shape peripheral physiology and end organ functioning. The growing knowledge on the neurobiology of the placebo/nocebo response will also affect the design of clinical trials in which treatment is tested against a placebo. Finally, it might affect our health care system not only by initiating a discussion on the ethical dimension of placebo treatment but also by forcing us to reconsider the significance of the placebo in clinical training and practice.

The dynamic progress in this field is not only reflected in the constantly growing number of publications explicitly focusing on the neurobiology and psychology of the placebo response, but also in the structure and content of scientific meetings on this topic. A 1999 symposium on the Mechanisms of Placebo covered this research area with two presentations on "expectation/conditioning mechanisms" and "opioid mechanisms" (9th World Congress on Pain, Vienna). In 2000, a NIH-sponsored workshop assembled ten presenters (and more than 500 attendants and discussants), mainly from the US, to cover the field and to assess the state of the art (Guess et al., 2002). A more recent symposium on the Mechanisms of Placebo/Nocebo Response held in Tutzing, Germany, in 2007 and supported by the Volkswagen Foundation, one of the major German research funding agencies, brought together 45 speakers and experts from eight countries with topics like "general concepts," "learning and memory," "brain-immune interaction," "Parkinson's disease and reward mechanisms," "pain," and "clinical-ethical implications," which reflect the steady growth of knowledge in this research field.

This review summarizes (1) current neurobiological models of the placebo response: expectations and reward, Pavlovian conditioning, and anxiety mechanisms of the nocebo response; (2) implications of insights into the placebo mechanisms for clinical trials and testing; and (3) the main research questions currently being discussed.

Comprehensive reviews focusing on the psychological (Price et al., 2008; Klosterhalfen and Enck, 2006), neuropharmacological/neuroanatomical (Colloca and Benedetti, 2005; Benedetti et al., 1995; Pacheco-Lopez et al., 2006; Benedetti, 2008) and methodological aspects of the placebo response (Colloca et al., 2008; Klosterhalfen and Enck, 2008) have been recently published elsewhere.

Current Models of the Placebo Response

A major insight from the recent publications on placebo is that there seems not to be a single neurobiological or psychobiological mechanism which is able to explain placebo and nocebo phenomena in general. Instead, we have learned that different mechanisms exist by which placebo or nocebo responses are steered across diseases and experimental conditions.

Expectation and the Brain Reward Circuitry

It has been proposed that the placebo effect is mediated by the brain reward circuitry (de la Fuente-Fernández et al., 2001; de la Fuente-Fernández and Stoessl, 2002). Based on placebo studies with Parkinson's patients (de la Fuente-Fernández et al., 2004) and in experimental pain (Scott et al., 2007), it has been hypothesized that reward expectations, such as expectation of clinical improvement, are likely to play an important role in the placebo effect. Thus, expectation may be closely tied to a tonic activation of tegmental or prefrontal dopaminergic neurons, which project to the dorsal and ventral striatum. In the expectation phase, prior to reward, there is uncertainty, and this is reflected in sustained dopaminergic activation, which is maximized when the probability of reward is 0.5. It is known that with a 0.5 probability of reward, 29% of dopaminergic cells are tonically activated (Fiorillo et al., 2003). Conversely, both occurrence and nonoccurrence lead to virtually no tonic activation. There is also phasic dopaminergic activation which takes place after reward, and this is stronger when the reward has come as a surprise. Therefore, uncertainty appears to heighten reward mechanisms in this brain reward circuitry model.

Based on this information, the following neurobiological placebo mechanism has been proposed (de la Fuente-Fernández, 2004; de la Fuente-Fernández et al., 2004). When an interaction (e.g., positive verbal suggestion) creates the possibility of a reward, which in the case of placebo administration is represented by the therapeutic benefit, certain cortical neurons become active in relation to reward probability. These cells send direct excitatory glutamatergic inputs to dopaminergic cell bodies along with indirect inhibitory gamma amino butyric acid inputs (de la Fuente-Fernández et al., 2002a; Fricchione and Stefano, 2005). The combination of these signals arriving at the dopaminergic neurons via direct and indirect pathways contributes to the probability of tonic activation (de la Fuente-Fernández et al., 2002b). Furthermore, it has been reported that neurons in the prefrontal cortex, nucleus accumbens, and the caudate-putamen display tonic activation during expectation of reward (Schultz, 1998).

Compelling evidence of the involvement of reward mechanisms in the placebo effect comes from recent brain imaging studies on placebo analgesia. In fact, in a brain imaging study in which both positron emission tomography and functional magnetic resonance imaging were used, Scott et al. (2007) tested the correlation between the responsiveness to placebo and that to monetary reward. By using a model of experimental pain in healthy subjects, they found that placebo responsiveness was related to the activation of dopamine in the nucleus accumbens, as assessed by using in vivo receptor-binding positron emission tomography with raclopride, a D2-D3 dopamine receptor agonist. The very same subjects were then tested with functional magnetic resonance imaging for activation in the nucleus accumbens to monetary rewards. What these investigators found is a correlation between the placebo responses and the monetary responses: the larger the nucleus accumbens responses to monetary reward, the stronger the nucleus accumbens responses to placebos.

This study strongly suggests that placebo responsiveness depends on the functioning and efficiency of the reward system, and this would explain, at least in part, why some individuals respond to placebos whereas some others do not. Those who have a more efficient dopaminergic reward system would also be good placebo responders. Interestingly, Scott et al. (2007) used an experimental approach that is typical of clinical trials, whereby the subjects know they have a 50% chance to receive either placebo or active treatment, and whereby no prior conditioning was performed.

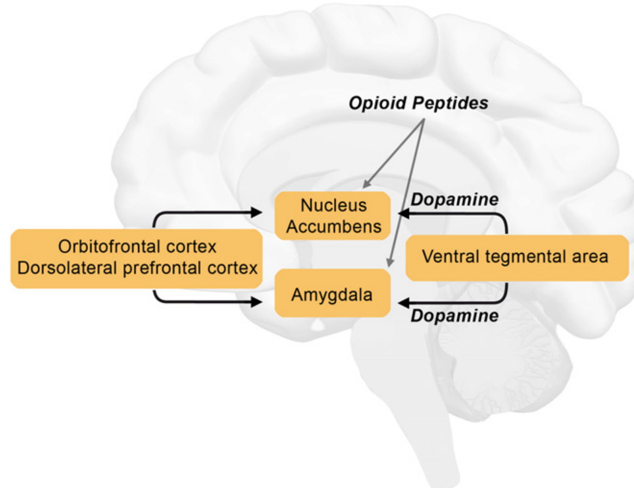

Figure 1. Simplified Scheme of the Reward System
Placebo administration has been found to activate both dopamine and endogenous opioid peptides in the nucleus accumbens, thus suggesting an involvement of reward mechanisms in some types of placebo effects (de la Fuente Fernández et al., 2001; Scott et al., 2008). Note: the main propose of this sketch is to focus on neural substrates of the reward system in the context of the placebo response which, in this case, takes precedence over anatomical accuracy.

In a different study by the same group, Scott et al. (2008) studied the endogenous opioid and the dopaminergic systems in different brain regions, including those involved in reward and motivational behavior. Subjects underwent a pain challenge, in the absence and presence of a placebo with expected analgesic properties. By using positron emission tomography with ^{11}C-labeled raclopride for the analysis of dopamine and ^{11}C-carfentanil for the study of opioids, it was found that placebo induced activation of opioid neurotransmission in the anterior cingulate, orbitofrontal and insular cortices, nucleus accumbens, amygdala, and periaqueductal gray matter. Dopaminergic activation was observed in the ventral basal ganglia, including the nucleus accumbens. Both dopaminergic and opioid activity were associated with both anticipation and perceived effectiveness of the placebo. Large placebo responses were associated with greater dopamine and opioid activity in the nucleus accumbens. Therefore, as shown in the schema of the reward circuitry in Figure 1, both dopamine and endogenous opioids have been found to be activated in the nucleus accumbens after placebo administration, which indicates that these two neurotransmitters play a key role in the modulation of the placebo response.

Pavlovian Conditioning of Placebo Effects: Neuroimmune Responses

The behavioral conditioning of immune responses is based on the intense crosstalk between the CNS and the peripheral immune system (Meisel et al., 2005; Sternberg, 2006; Tracey, 2007). Commonly, in these approaches, experimental animals are presented with a novel taste (e.g., saccharin) as conditioned stimulus (CS) in the drinking water, and subsequently injected with an agent that produces changes in immune status (unconditioned stimulus, UCS). When the CS (saccharin solution) is re-presented at a subsequent time point, the animals avoid drinking the saccharin, which is termed ''conditioned taste aversion'' (CTA) (Garcia et al., 1955). Concomitantly, the animals demonstrate a modification of immune parameters that commonly mimics the actual UCS effect (Ader, 2003). Ader and Cohen (1975) demonstrated conditioned suppression of antibody production for the first time. Experimental evidence over the last 25 years has shown behaviorally conditioned effects in rodents, both in humoral and cellular immunity, with behavioral conditioning able to re-enlist changes in lymphocyte circulation and proliferation, cytokine production, natural killer (NK) cell activity, and endotoxin tolerance (reviewed in Exton et al., 2001; Ader, 2003; Pacheco-Lopez et al., 2006; Riether et al., 2008).

Regarding the neurobiological mechanisms, it was demonstrated by employing the immunosuppressant cyclophoshamide as a UCS that the insular cortex and the amygdala are key structures in behaviorally conditioned suppression of antibody production (Ramírez-Amaya et al., 1996, 1998). In parallel, when the calcineurin inhibitor and immunosuppressive agent cyclosporine A was employed as a UCS in a taste aversion paradigm, the behaviorally conditioned suppressive effect on lymphocyte activity in the spleen, as well as cytokine production (interleukin-2, interferon-γ), was affected by brain excitotoxic lesions. This shows that the insular cortex is essential to acquiring and evoking this conditioned response in cellular immune functions. In contrast, the amygdala seems to mediate the input of visceral information necessary at acquisition time, whereas the ventromedial hypothalamic nucleus appears to participate in the output pathway to the immune system, which is needed to evoke the behaviorally conditioned immune response (Pacheco-Lopez et al., 2005). On the peripheral efferent arm, these conditioned effects are mediated via the splenic nerve through noradrenaline and adrenoceptor-dependent mechanisms (Exton et al., 2001, 2002). The neural circuitry is illustrated in Figure 2.

A number of studies have meanwhile demonstrated the clinical relevance of conditioned changes in immune function. Specifically, the morbidity and mortality of animals with autoimmune disease was abated via conditioning using cyclophosphamide (Ader and Cohen, 1982) or with cyclosporine (Klosterhalfen and Klosterhalfen, 1990) as the UCS and, in addition, behavioral conditioning prolonged the survival of heterotopic heart allograft and significantly inhibited the contact hypersensitivity reaction (Exton et al., 1998, 1999, 2000).

Experimental evidence also suggests that behavioral conditioning of immunopharmacological drug effects is possible in humans. Conditioned cyclosphosphamide-induced leucopenia has been reported (Giang et al., 1996), along with a conditioned immune response to the cytokine interferon-γ (Longo et al., 1999), as well as conditioned suppression of the ex vivo production and mRNA expression of interleukin-2 and interferon-γ, and of the proliferation of peripheral lymphocytes (Goebel et al., 2002). Allergic reactions have been shown to be affected by behavioral conditioning and emotional status (Kemeny et al., 2007). However, more recently, it was demonstrated that the antihistaminergic properties of the H_1-receptor antagonist desloratadine can be behaviorally conditioned in patients suffering from allergic house-dust-mite rhinitis, as analyzed by subjective symptom score, skin prick test, and decreased basophile activation (Goebel et al., 2008). Interestingly, subjective symptom score and skin reactivity, but not basophile activation, was reduced in patients who where conditioned but not re-exposed to the novel-tasting drink served as a CS. By contrast, only conditioned patients who were re-exposed to the CS also demonstrated significant inhibition in cellular immune activation. These data support earlier observations indicating that conscious physiological pain and motor mechanisms are mainly affected by patients' conscious expectations, whereas unconscious physiological processes, such as hormone release or immune functions, appear to be mediated by behavioral conditioning (Benedetti et al., 2003).

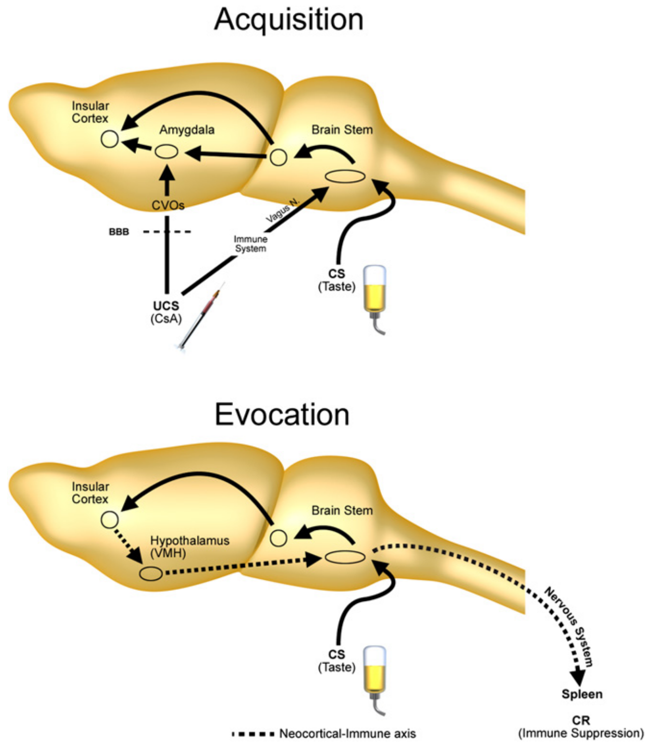

Figure 2. Neural Substrates Involved in Behaviorally Conditioned Immunosuppression in Rats
Brain excitotoxic lesions show that the insular cortex is essential to acquiring and evoking this conditioned immunosuppressive response. In contrast, the amygdala seems to mediate the input of visceral information necessary at acquisition time, whereas the ventromedial hypothalamic nucleus appears to participate in the output pathway to the immune system needed to evoke the behaviorally conditioned immune response (CS, conditioned stimulus, saccharin taste; UCS, unconditioned stimulus; CsA, cyclosporine A; BBB, blood-brain barrier; CVOs, circumventricular organs; VMH, ventromedial hypothalamic nucleus) (Pacheco-Lopez et al., 2005).

Similar conditioning mechanisms have been found in the endocrine system. In one study aimed at differentiating the effects of conditioning and expectation, plasma levels of both growth hormone and cortisol were measured in different conditions (Benedetti et al., 2003). In the first experimental condition, verbal suggestions of growth hormone increase and cortisol decrease were delivered to healthy volunteers, so as to make them expect hormonal changes. These verbal instructions did not have any effect on both hormones, and in fact no plasma concentration change was detected. In the second experimental condition, sumatriptan, a serotonin 5-$HT_{1B/1D}$ receptor agonist that stimulates growth hormone and inhibits cortisol secretion, was administered for 2 days in a row and then replaced with a placebo on the third day. A significant increase of growth hormone and decrease of cortisol plasma concentrations were found after placebo administration. These conditioned effects occurred regardless of the verbal suggestions the subjects received. In other words, the placebo mimicked the sumatriptan-induced growth hormone increase, even though the subjects expected a growth hormone decrease. Likewise, the placebo mimicked the sumatriptan-induced cortisol decrease, even though the subjects expected a cortisol increase. It can be assumed that in this case the conditioned stimulus was represented by the act of injecting the pharmacological agent (i.e., the context around the treatment).

This experimental evidence demonstrates the potential applicability of such behavioral conditioning protocols in clinical practice. However, in future studies it will be necessary to analyze the kinetics of the behaviorally conditioned immunopharmacological and endocrine response and to elucidate whether and to what extent these conditioned responses can be reconditioned on multiple occasions. Only with this information and more detailed knowledge of the mechanisms behind the CNS-immune system and CNS-endocrine system interaction will it be possible to design conditioning protocols which can be employed in clinical situations to the patients' advantage.

Mechanisms of the Nocebo Effect

Compared to the placebo effect, much less is known about the nocebo effect, since the induction of a nocebo response represents a stressful and anxiogenic procedure, thus limiting its ethical investigation. The term nocebo (''I shall harm'') was introduced in contraposition to the term placebo (''I shall please'') by a number authors in order to distinguish the pleasing from the noxious effects of placebo (Kennedy, 1961; Kissel and Barrucand, 1964; Hahn, 1985, 1997). If the positive psychosocial context, which is typical of the placebo effect, is reversed, the nocebo effect can be studied. Therefore, it is important to stress that the study of the nocebo effect relates to the negative psychosocial context surrounding the treatment, and its neurobiological investigation is the analysis of the effects of this negative context on the patient's brain and body. As for the placebo effect, the nocebo effect follows the administration of an inert substance, along with the suggestion that the subject will get worse. However, the term nocebo-related effect can also be used whenever symptom worsening follows negative expectations without the administration of any inert substance (Benedetti et al., 2007b; Benedetti, 2008).

Brain imaging techniques have been crucial to understanding the neurobiology of negative expectations, and most of this research has been performed in the field of pain. Overall, negative expectations may result in the amplification of pain (Koyama et al., 1998; Price, 2000; Dannecker et al., 2003) and several brain regions, like the anterior cingulate cortex (ACC), the prefrontal cortex (PFC), and the insula, have been found to be activated during the anticipation of pain (Chua et al., 1999; Hsieh et al., 1999; Ploghaus et al., 1999; Porro et al., 2002, 2003; Koyama et al., 2005; Lorenz et al., 2005; Keltner et al., 2006). For example, Sawamoto et al. (2000) found that expectation of a painful stimulus amplified the perceived unpleasantness of innocuous thermal stimulation, and that these subjective hyperalgesic reports were accompanied by increased brain activations in the anterior cingulate cortex (ACC), the parietal operculum (PO), and posterior insula (PI). In another study by Koyama et al. (2005), as the magnitude of expected pain grew, activation increased in the thalamus, insula, PFC, and ACC. By contrast, expectations of decreased pain reduced activation of pain-related brain regions, like the primary somatosensory cortex, the insular cortex, and ACC. Likewise, Keltner et al. (2006) found that the level of expected pain intensity altered the perceived intensity of pain along with the activation of different brain regions, like the ipsilateral caudal ACC, the head of the caudate, the cerebellum, and the contralateral nucleus cuneiformis (nCF).

Besides neuroimaging, pharmacological studies give us insights into the biochemistry of the nocebo effect and of negative expectations. For example, the antagonist action of CCK on endogenous opioids (Benedetti, 1997) is particularly interesting in the light of the opposing effects of placebos and nocebos. A model has recently been proposed whereby the opioidergic and the CCK-ergic systems may be activated by opposite expectations of either analgesia or hyperalgesia, respectively. In other words, verbal suggestions of a positive outcome (pain decrease) activate endogenous μ-opioid neurotransmission, while suggestions of a negative outcome (pain increase) activate CCK-A and/or CCK-B receptors. This neurochemical view of the placebo-nocebo phenomenon, in which two opposite systems are activated by opposite expectations about pain, is in keeping with the opposite action of opioids and CCK in other studies (Benedetti et al., 2007a). Interestingly, the CCK-antagonist proglumide has been found to potentiate placebo-induced analgesia, an effect that is probably due to the blockade of the anti-opioid action of CCK (Benedetti et al., 1995; Benedetti, 1996). Therefore, CCK appears to play a pivotal role in the psychological modulation of pain, antagonizing placebo-induced opioid release on the one hand and mediating nocebo-induced facilitation of pain on the other hand.

The involvement of CCK in nocebo hyperalgesia is likely to be mediated by anxiety, as benzodiazepines have been found to block both nocebo-induced hyperalgesia and the typical anxiety-induced hypothalamus-pituitary-adrenal hyperactivity. Conversely, the CCK antagonist, proglumide, has been found to prevent nocebo hyperalgesia but not the hypothalamus-pituitary-adrenal hyperactivity, which suggests two independent biochemical pathways activated by nocebo suggestions and anxiety (Figure 3).

More recent studies have found that nocebo effects are also associated to a decrease in dopamine and opioid activity in the nucleus accumbens, thus underscoring the role of the reward and motivational circuits in nocebo effects as well (Scott et al., 2008). In other words, the activation/deactivation balance of both dopamine and opioids in the nucleus accumbens would account for the modulation of placebo and nocebo responses. Therefore, a complex interaction among different neurotransmitters, such as CCK, dopamine, and opioids, occurs when either placebos or nocebos are administered.

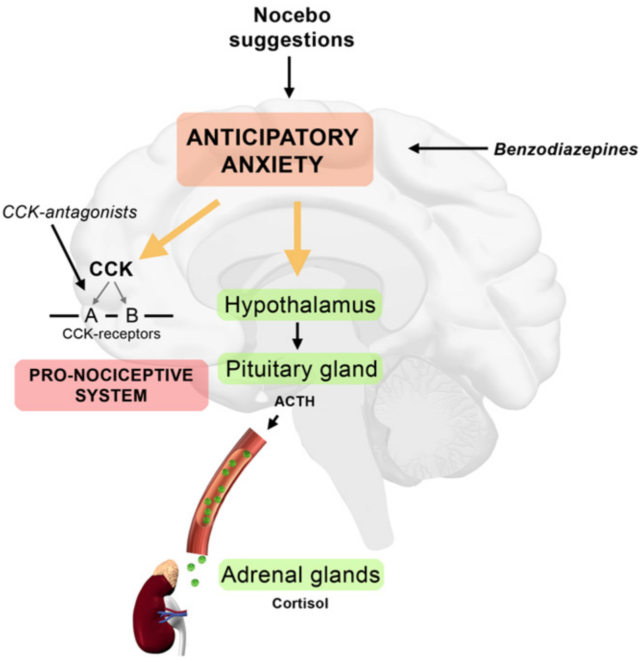

Figure 3. Mechanisms of the Hyperalgesic Nocebo Effect
Nocebo suggestions induce anticipatory anxiety, which activates two independent pathways, the hypothalamus-pituitary-adrenal (HPA) axis on the one hand and a CCK-ergic pronociceptive system on the other hand. Benzodiazepines act on anxiety, thus blocking both the HPA hyperactivity and the CCK pronociceptive system. In contrast, CCK antagonists act on the pronociceptive system only, thus preventing nocebo hyperalgesia but not HPA-hyperactivity (Benedetti et al., 2006). Note: the main propose of this sketch is to focus on neural substrates of the hyperalgesic nocebo effect which, in this case, takes precedence over anatomical accuracy.

Placebo Responses in Clinical Trials

Ever since the dawn of the first randomized placebo-controlled trials testing new drugs and treatments in the middle of the last century, and even before (Hill, 1990), placebo responses in clinical trials have given rise to discussion and concern regarding their mechanisms and have usually been regarded as a nuisance or a barrier to a rational approach in modern drug development. High placebo responses have induced false expectations regarding drug efficacy and resulted in the refusal of drug approval in some cases, e.g., neurokinins in the treatment of depression (Kramer et al., 1998; Enserink, 1999).

Not only do placebo responses in clinical trials impose significant limits to the testing of new compounds, but they are also linked to the drug adherence and compliance of patients in such trials in a paradoxical way. Patients that adhered to medication instructions by more than 80% showed better survival in a coronary disease study (Coronary Drug Project Research Group, 1980), and poor drug adherence in a myocardial infarction survivor study was associated with a higher risk of mortality (Beta-Blocker Heart Attack Trial, Horwitz et al., 1990), irrespective of whether the active compound or a placebo was taken, and regardless of other potential risk factors. This has been attributed to the greater expectancies or beliefs, both in drug and placebo responders that the medication may be of help, although other factors, such as health behaviors, cannot be ruled out completely. These findings have certainly fostered the development of further experimental approaches to the placebo phenomenon.

Attempts to unravel the mechanisms of the placebo response in clinical trials have used meta-analytic approaches of the placebo arm of trials—with mixed results. The placebo effect in randomized controlled trials has been reported to be around 40% in functional disorders (Enck and Klosterhalfen, 2005) but lower in depression (29%), bipolar mania (31%) (Sysko and Walsh, 2007), and migraine (21%) (Macedo et al., 2008). The reasons for these variable placebo response rates are unknown but may include the sample size (Enck and Klosterhalfen, 2005), the year of study (Walsh et al., 2002), design characteristics (Macedo et al., 2006), and recruitment pattern (Kobak et al., 2007). Meta-analyses can come to opposite conclusions on the same data set, e.g., with respect to the direction of the effects of the number of study visits on the placebo effect size (e.g., Pitz et al., 2005; Patel et al., 2005), but this may be due to data extraction errors that lead to false findings and conclusions (Gøtzsche et al., 2007). Hróbjartsson and Gøtzsche (2001, 2004) came to conclude that the placebo response appears to be powerful only because of a lack of "no treatment" control groups in most studies. However, their argument has been challenged by data indicating that among the trials they included into their meta-analyses, those with endpoints regulated directly by the autonomic nervous system do report stronger response to placebo treatment, while endocrine and other endpoints are less responsive (Meissner et al., 2007).

Other contributing factors to the placebo response rate in clinical trials were: the origin of patients—response rates in migraine prophylaxis were higher in Europeans than in North Americans (Macedo et al., 2008), personal expectations (Linde et al., 2007) and the loss thereof, e.g., in Alzheimer's disease (Benedetti et al., 2006), the study center (Ondo, 2007), and patient recruitment and physician training (Kobak et al., 2007). A genetic contribution to placebo responsiveness has been proposed (Bendesky and Sonabend, 2005; Raz, 2008) but empirical evidence is still lacking.

Because of the difficulties to reliably identify placebo responders and predicting placebo response rates in clinical trials, different methodological attempts have been made to the way (novel) drugs are tested against placebo.

The most traditional way to attempt to control for placebo response in clinical trials was the use of a crossover design, in which an individual patient serves as her/his own control, reducing the between-subject variability and the number of patients studied. This model was almost completely abolished due to the fact that blinding may be rather difficult in such studies (Boutron et al., 2006), unless one is able to implement "active placebos" that mimic the side-effects of a compound without inducing its main effects (Edward et al., 2005). Another conventional model to control for placebo effects is the use a placebo run-in phase prior to drug and placebo dispensing to identify and exclude placebo responders: placebo responders tend to exhibit less severe symptoms during run-in (Evans et al., 2004) and to respond faster to treatment with symptom improvement (Gomeni and Merlo-Pich, 2007) than patients in the drug arm. Drug-free run-in periods have also been used to identify individual and group characteristics of placebo responders. However, these results are not generalizable across medical conditions, (Talleyn et al., 2006) since most of the variables that are regularly documented at study initiation are related to symptoms and disease characteristics rather than to individual personality traits or states (Hyland et al., 2007). An extension of placebo run-in periods are studies with multiple drug/placebo phases that alternate, with or without washout periods in between (Kleveland et al., 1985). These models were more recently requested again by drug approval authorities to account for variable symptom courses and the alternation of symptom-free with relapse periods in many chronic diseases. It has, however, been shown that the placebo response in a first medication period does not reliably predict the response (to drug or placebo) in a second phase (Tack et al., 2005). If being a placebo responder is a characteristic of an individual patient, study designs should take this into account by employing a design with multiple (>2) crossovers between placebo and drug and to randomize and individualize in a "single-subject trials" (SST) the timing for run-in and run-out for each phase (Madsen and Bytzer, 2002). In theory, this should allow us to reliably distinguish placebo responders from nonresponders. However, multiple crossovers with randomly assigned treatment periods, with a complete random order or a random starting day generate specific methodological problems and need new statistical models before being applicable in clinical drug testing.

In experimental laboratory research, a number of experimental designs have been employed that may help to identify predictors of the placebo response in the future. The so-called "balanced placebo design" (BPD) was traditionally used in the testing for placebo effects of frequently consumed everyday drugs such as caffeine, nicotine, and alcohol (e.g., Dagan and Doljansky, 2006; Kelemen and Kaighobadi, 2007; Cole-Harding and Michels, 2007). While one-half of the study sample receives placebo and the other half the drug, half of each group is receiving correct information while the other half is receiving false information on the nature of their study condition (drug or placebo) immediately prior to drug testing, thus allowing to differentiate between the "true" drug effect (those receiving the drug but are told they received placebo) and the true placebo effect (those receiving placebo but are told they received the drug). As is evident, the BPD implies "deception" of the subjects (Miller et al., 2005), which limits its suitability and acceptance outside the laboratory and in patients for ethical reasons (Ehni and Wiesing, 2008).

Hidden treatment (HT) or covert treatment is another option that may be specifically useful for the test of drug effects in acute and highly symptomatic conditions such as with postoperative pain (Levine et al., 1981), anxiety, and motor dysfunction in Parkinson's disease (Benedetti et al., 2004b; Lanotte et al., 2005). It resembles some of the features of the SSTs (Madsen and Bytzer, 2002). In case of HT, the patient may receive a drug unnoticed in terms of timing and dosage, and the drug effect (or its missing action) can be determined independent of the patient's expectations. Benedetti and colleagues demonstrated that under these circumstances drugs commonly believed to have analgesic properties such as CCK-antagonists failed to show any antinociceptive effects (Colloca et al., 2004). Evidently, HT can only be applied with the patient agreeing prior to the test that she/he may or may not receive a drug at all, which may raise other ethical concerns (Machado, 2005), especially with the test of novel compounds of unknown properties.

Finally, a free-choice paradigm (FCP), which maybe regarded as a modification of the adaptive response design (Rosenberger and Lachin, 1993) or the early-escape design (Vray et al., 2004) may offer an alternative approach to common drug test procedures. FCP allows the patient to choose between two pills, of which one is the drug and one the placebo, at medication-dispensing time; it is, however, essential that the patient does not take both pills at the same time (hence, a technical or administrative modus has to be implemented to prevent this and to prevent over-dosage etc.), and that he/she may switch to the other condition at any time (hence, the pharmacodynamics of the compound under investigation have to be appropriate, e.g., the speed of action, the feasibility of on-demand medication, etc.). It would, on the other hand, allow assessment of drug efficacy via the choice behavior rather than with symptomatic endpoints. The FCP has been used occasionally in optimizing dosage of drugs (Perkins et al., 1997; Pinsger et al., 2006) in clinical trials. It bypasses many of the ethical concerns against the use of placebos (Ehni and Wiesing, 2008), but its methodology and statistics in assessing drug superiority over placebo have not been validated (Zhang and Rosenberger, 2006).

Research Questions for Future Research

The experimental work on the neurobiological and neuropsychological mechanisms of the placebo/nocebo response from the last decade has impressively increased our knowledge of this long-known phenomenon. It became clear that these approaches will not only help us to better understand human physiology but might have many practical consequences such as on the design of clinical studies, our health care systems, in particular the doctor-patient relationship as well as the education of medical care professionals. However, there are still numerous open questions which urgently need to be addressed in future studies.

The Relationship between Suggested and Conditioned Placebo Effects

It has been postulated that the placebo response is generated by two distinct mechanisms across clinical conditions, one of which concerns suggestion and expectation, and one learning via Pavlovian conditioning (Benedetti et al., 2003; Klosterhalfen and Enck, 2006). The relationship between these two is still unclear, but it has been the subject of experimental research in recent years. Benedetti et al. (2003) were able to demonstrate in experimental pain and in Parkinson's disease that conditioning is actually mediated by expectations and that expectations do not affect conditioned responses. Similar explanations have been put forward, for example, that expectancies acquired through verbal instructions might also be seen as conditioning stimuli that reactivate earlier stimulus association (Klinger et al., 2007).

In a set of experiments, it has recently been demonstrated that prior experience is able to shape placebo analgesia (Colloca and Benedetti, 2006). Subjects that were conditioned to experience placebo analgesia in an acute paradigm showed reduced pain experiences for up to seven days and exhibited no extinction of responses in the range of minutes. However, placebo analgesia was reduced by prior exposure to negative painful experience. These data emphasize that previous experience with the treatment of pain, both successful and unsuccessful, will have lasting effects on how the second and subsequent treatments of the same conditions are perceived. The analogy to clinical conditions is evident, but relative. While experimental pain is phasic and acute, clinical pain is usually chronic, long-lasting. Whether and to what degree previous pain treatment contributes to the experience of placebo analgesia in a clinical trial—usually 15%–20% of the effect size achieved under experimental pain conditions (Vase et al., 2002)—probably needs to be tested with a different experimental or clinical design. When experimental placebo analgesia was directly compared to pain relief in pain patients, the data suggested that mechanisms counteracting the proanalgesic effects of placebo suggestions are involved (Charron et al., 2006).

It is puzzling to realize that, beyond the laws of Pavlovian learning studied for almost a century now, there is basically no model available that allows us to predict the maintenance of a strong placebo response in a clinical trial that may last for a year or longer (e.g., Chey et al., 2004). According to these laws (Zimmer-Hart and Rescorla, 1974), any conditioned response should diminish over time if no further pairing of the UCS (e.g., an effective drug) and the CS (a pill or injection) occurs but the CS is presented alone. In such trials, extinction does not seem to occur at all. Hence, one may speculate that if conditioning (learning) is part of this placebo response, it cannot be of a Pavlovian nature. Alternatively, in the case of newly developed compound, previous experience with a drug, or a similar compound, that might shape the response can have been gained only by generalization.

The other issue that requires attention is the clinical applicability of conditioned and suggested placebo responses in daily medicine, as many of the studies have so far been conducted in the laboratory and with healthy subjects. One example of a successful transfer from bench to bedside, however, has been documented by studies demonstrating behaviorally conditioned effects in peripheral immune responses (see above).

Is There a Consistent Brain Network for All Placebo Effects?

The number of brain imaging studies on the placebo response has increased greatly over the past few years, in particular in the area of pain and placebo analgesia (Petrovic et al., 2002; Wager et al., 2004; Bingel et al., 2006; Kong et al., 2006; Price et al., 2006), but also to a lesser degree with regard to neurological and psychiatric diseases, such as Parkinson's disease, depression, or irritable bowel disorder (reviewed, e.g., by Benedetti et al., 1995; Colloca and Benedetti, 2005; Beauregard, 2007; Lidstone and Stoessl, 2007, Enck and Klosterhalfen, 2005).

As to experimental pain, different cortical (prefrontal cortex, anterior cingulate gyrus, insula, supplementary motor area), and subcortical structures (amygdala, periacqueductal gray, thalamus) have been found to be involved in the placebo response, and they seem to differentiate between the sensory and the emotional/affective components of pain signals. PET receptor-binding studies have provided direct evidence that the μ-opioid system involving the brain stem and elaborated cortical networks mediates placebo analgesia (Zubieta et al., 2005; Wager et al., 2007), thus confirming previous studies on the blockade of placebo analgesia by the opioid antagonist naloxone (Levine et al., 1978; Amanzio and Benedetti, 1999). It should be noted that other neurochemical systems have been found to contribute to the placebo effect, e.g., the dopaminergic system (Scott et al., 2007, 2008) and CCK (Benedetti et al., 1995; Benedetti, 1996). It remains unclear, however, whether each of these systems contributes to all placebo responses or only to those under specific clinical and experimental conditions. Placebo responses in Parkinson's disease and pain have been linked to a subcortical dopaminergic "reward" in the ventral striatum (de la Fuente-Fernández et al., 2001; Scott et al., 2007); however, the involvement of dopamine was recently questioned with regard to the placebo response in experimental pain (Martikainen et al., 2005). Nevertheless, it is worth mentioning that a possible downstream effect of dopamine activation after placebo administration was found in the subthalamic nucleus, in which single neurons changed their firing pattern (Benedetti et al., 2004a).

It is one of the drawbacks of imaging studies that they rely on a stable and dominant activation pattern across all subjects, since group means are necessary for adequate data analysis. Therefore, placebo nonresponders in small samples of subjects are frequently excluded or used as a type of control (Petrovic et al., 2002; Leuchter et al., 2002; Nemoto et al., 2007). Assessment of individual responsiveness to placebo (Chung et al., 2007) is, however, necessary to advance the field.

Other neurophysiological and psychobiological mechanisms of placebo analgesia and placebo response are currently being discussed. Placebo analgesia following heat pain application may change spinal cord pain processing via descending pathways (Matre et al., 2006), and expectations have been found to alter spinal reflexes and the descending noxious inhibitory control (Goffaux et al., 2007). This raises an important issue that needs to be addressed in future research: While for expectation-induced placebo responses, higher centers of the CNS are needed, Pavlovian conditioning may also occur within the peripheral neural circuitry, e.g., within the enteric nervous system (Drucker and Sclafani, 1997). Whether this also relates to conditioned placebo responses warrants further research.

The Role of Gender in Placebo Effects

Gender effects of the placebo response have rarely been documented in clinical trials but have occasionally been noted in experimental settings (Flaten et al., 2006). However, whether and to what extent gender differences may account for some of the variance in the placebo imaging studies is unknown so far. Cortical processing, independent of the placebo response, has shown significant gender variation both in volunteers and in patients with somatic and visceral pain (Paulson et al., 1998; Berman et al., 2000) and with nonpainful stimuli (Sabatinelli et al., 2004; Gizewski et al., 2006). Unfortunately, most imaging studies on the placebo response have ignored the potential role of gender (Klosterhalfen and Enck, 2008).

Gender effects in the placebo response were reported in an experimental setting with placebo analgesia during ischemic pain, whereby males responded to the manipulation of expectancies through pain information, while women did not (Flaten et al., 2006). However, an experimenter effect could not be excluded, as all the experimenters were female nurses, which could have induced a reporting bias (Kallai et al., 2004). Gender effects were also noted in an acupuncture trial with male and female acupuncturists, with females inducing greater trust than male experimenters (White et al., 2003). Employing a motion-sickness paradigm, conditioning was effective predominantly in women, while in the suggestion experiment, men exhibited a significantly greater reduction in rotation tolerance and responded more strongly to rotation and to suggestions than women (Klosterhalfen et al., 2007). However, other data from this group pointed toward the role of biological factors (e.g., the menstrual cycle) on processing of visceral and vestibular sensations (Klosterhalfen et al., 2008b) and on differential effects of stress hormone release on nausea and motion sickness (Rohleder et al., 2006). These observations clearly show the necessity to investigate gender effects in the placebo and nocebo responses.

The Impact of Obtaining Drug-like Effects without Drugs

One of the most practical implications of the recent neurobiological advances in placebo research is the possibility to induce, at least in some circumstances, drug-like effects without the administration of drugs. Throughout this review we have seen that placebos can induce the activation of endogenous opioids and dopamine, that placebo-conditioned responses of several immune mediators can be obtained through behavioral conditioning, and that nocebos activate the endogenous CCK-ergic systems. The obvious consequence of these findings is their exploitation both in the clinic and in other areas of society, although important ethical constraints have so far limited the development of therapeutic paradigms with placebos.

As far as the clinic is concerned, it would be conceivable today to use a translational approach whereby many experimental protocols, so far carried out in animals and healthy volunteers, could be applied to real medical conditions. For example, there is compelling evidence that pharmacological conditioning can induce powerful placebo responses when the real drug is replaced with a placebo. This phenomenon is well documented in humans, for example in pain (Amanzio and Benedetti, 1999), the immune system (Goebel et al., 2002), and the endocrine and motor systems (Benedetti et al., 2003), although unfortunately no systematic investigation has been done in a real clinical setting. There are, however, some indications that the application of placebo-induced drug-like effects without drugs is possible in the clinic. For example, Benedetti et al. (2004a) conditioned Parkinson's patients with repeated administrations of the anti-Parkinson's drug apomorphin before the surgical implantation of electrodes for deep brain stimulation. Then, the investigators replaced apomorphin with a placebo in the operating room and obtained a powerful placebo reduction of muscle rigidity that mimicked the effects of apomorphin during the previous days. Although the effect was short-lasting (no longer than 20–30 min), it was useful from a clinical point of view because the patient improved and felt better for a while, thus making some surgical procedures easier and faster. These drug-mimicking effects could be particularly useful whenever the drug has important side effects. For example, in the study by Benedetti et al. (2004a), the presurgical apomorphin resulted in both clinical improvement and some side effects, like dyskinesia, whereas the placebo in the operating room induced improvement but not dyskinesia.

Besides the clinic, there are also some other areas of society in which the drug-like effects of placebos may have a strong impact. In a very recent study, Benedetti et al. (2007b) used placebos in an experimental simulation of a sporting event, whereby a placebo was given on the competition day after preconditioning with a narcotic in the training phase. In fact, after repeated administrations of morphine in the training phase, its replacement with a placebo on the day of the competition induced an opioid-mediated increase in pain endurance and physical performance, even though no illegal drug was administered. This shows that athletes can be preconditioned with narcotics and then a placebo given just before the competition, thus avoiding the administration of illegal drugs on the competition day. These narcotic-like effects of placebos raise the important question of whether opioid-mediated placebo responses are ethically acceptable in sport or whether they should rather be considered as a doping procedure in all respects. In the light of the distinction between drugs that are prohibited during and/or out of competition, the preconditioning procedure may be deemed ethical and legal for drugs that are prohibited only during competition, like narcotics (World Anti-Doping Agency 2007, www.wada.ama.org). However, it may also be considered illegal because morphine administration is aimed at conditioning the subjects for subsequent replacement with a placebo, which is supposed to show morphine-like effects during the competition. This issue is not easy to be resolved and needs both an ethical and a legal discussion. In fact, doping is a matter of great public concern today, and we should be aware that if a procedure like the one described by Benedetti et al. (2007b) is performed, illegal drugs in sport would no longer be discoverable, nor would they violate the current antidoping rules.

Where Does Placebo Research Go from Here?

Despite the recent explosion of neurobiological placebo research using sophisticated tools, such as neuroimaging, in vivo receptor binding, and single-neuron recording in awake subjects, our knowledge of the mechanisms underlying the placebo effect is still in its infancy, and several issues need to be addressed in future research. The major questions to be answered are where, when, how, and why placebo effects occur. In fact, we need to know where they work exactly, that is, in which medical conditions. For example, are all diseases and symptoms subject to placebo effects? We also need to know when they work, that is, whether there are special circumstances that are particularly amenable to placebo effects. How they work is also a major question, as we need to understand the brain mechanisms at both the macroscopic (brain regions and their interactions with body functions) and microscopic (cellular and molecular) level. Finally, determining why placebo effects exist at all represents a major scientific challenge, and meeting that challenge will give us insights into the possible evolution of endogenous healthcare systems.

Besides the profound implications of placebo research for a better understanding of human biology, some practical aspects should not be forgotten. For example, placebo and nocebo phenomena are a major hurdle in the development and validation of new treatments, as high placebo responses sometimes distort the effects of a therapy. If we can identify in more detail the major mechanisms involved in placebo responsiveness, we could also develop strategies aimed at minimizing placebo effects, thereby uncovering the real effect of a therapy. Likewise, nocebo effects can be a serious drawback, as negative reactions to drugs are sometimes due to psychological effects rather than to specific negative effects of the drug itself. Therefore, research aimed at investigating nocebo mechanisms would enable us to disentangle the negative effects of the drug from those of the psychological state of the patient. In addition, a better understanding of the neurobiology of the placebo and nocebo responses will form the basis for designing behavioral protocols that can be employed as supportive therapy together with standard pharmacological regimen, the aim being to maximize the therapeutic outcome for the patient's benefit.

We believe that the future years will be characterized by a deeper understanding of both the placebo and nocebo phenomena, which in turn will give us profound insights into many aspects of human biology.

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Nocebo effects can make you feel pain:

Negative expectancies derived from features of commercial drugs elicit nocebo effects

Luana Colloca
University of Maryland, School of Nursing and School of Medicine, Baltimore, C655 W. Lombard Street Suite 729, 21201 Baltimore, MD

The mysterious phenomenon known as the nocebo effect describes the effects of negative expectancies. This is in contrast to positive expectations that trigger placebo effects (1). In evolutionary terms, nocebo and placebo effects coexist to favor perceptual mechanisms that anticipate threat and dangerous events (nocebo effects) and promote appetitive and safety behaviors (placebo effects). In randomized placebo-controlled clinical trials, patients that receive placebos often report side effects (nocebos) that are similar to those experienced by patients that receive the investigational treatment (2). Information provided during the informed consent process and divulgence of adverse effects contribute to nocebo effects in clinical trials (1). Nocebo (and placebo) effects engage a complex set of neural circuits in the central nervous system that modulate the perception of touch, pressure, pain and temperature (1, 3, 4). Commercial features of drugs such as price and labeling influence placebos (5, 6). On page 105 of this issue, Tinnermann *et al.* (7) show that price also impacts nocebo effects.

Tinnermann *et al.* evaluated the responses of healthy participants who received two placebo creams labeled with two distinct prices and presented in two boxes that had marketing characteristics for expensive and cheap medication. The creams were described as products that relieve itch but induce local pain sensitization (hyperalgesia). All creams, including controls, were identical and contained no active ingredients. Nocebo hyperalgesic effects were larger for the “more expensive” cream than for the “cheaper” cream. Combined cortico-spinal imaging revealed that the expensive price value increased activity in the prefrontal cortex. Furthermore, brain regions such as the rostral anterior cingulate cortex (rACC) and the periacqueductal gray (PAG), encoded the differential nocebo effects between the expensive and cheaper treatments. Expectancies of higher pain-related side effects associated with the expensive cream may have triggered a facilitation of nociception processes at early subcortical areas and the spinal cord [which are also involved in placebo-induced reduction of pain (8)]. The rACC showed a deactivation and favored a subsequent activation of the PAG and spinal cord resulting in an increase of the nociceptive inputs. This finding suggests that the rACC-PAG-spinal axis may orchestrate the effects of pricing on nocebo hyperalgesia (see the figure).

The anticipation of forthcoming painful stimulation makes healthy study participants perceive non-painful and low-painful stimulations as painful and high-painful, respectively (9). Verbally-induced nocebo effects are as strong as those induced through actual exposure to high pain (9). Moreover, receiving a placebo after simulating an effective analgesic treatment compared to receiving the same placebo intervention after a treatment perceived as ineffective produce a 49.3% versus 9.7% placebo induced pain reduction, respectively (10).

The relationship between prior either unsuccessful or successful pain relief interventions and placebo analgesic effects is linked to a higher activation of the bilateral posterior insulae, and reduced activation of the right dorsolateral prefrontal cortex (11).

Informing patients that a treatment has been stopped, compared to a covert treatment interruption, impacts the response to morphine, diazepan or deep brain stimulation in post-operative acute pain, anxiety or idiopathic Parkinson's disease, respectively (12). Patients openly informed about the interruption of each intervention experience a sudden increase of pain, anxiety or bradykinesia (a manifestation of Parkinson's disease), whereas a hidden interruption does not (12). Neuroimaging approaches support the clinical observation. For example, the action of the analgesic, remifentanil, is over-ridden by activation of the hippocampus that occurs when healthy participants that receive heat painful stimulations are misleadingly told that the remifentanil administration was interrupted (13). These findings provide evidence that communication of treatment discontinuation might at least in part, lead to nocebo effects with aggravation of symptoms.

In placebo-controlled clinical trials, nocebo effects can influence patients' clinical outcomes and treatment adherence. The Lipid-Lowering Arm of the Anglo-Scandinavian Cardiac Outcomes Trial shows that atorvastatin induced in the same individuals an excess rate of muscle-related adverse events in the non-blinded (ie. patients knew they were taking atorvastatin) non-randomized three year follow-up phase but not in the initial blinded five year phase when patients and physicians were unaware of the treatment allocation (atorvastatin or placebo) (14). Misleading information about side effects for statins via public claims has led to treatment discontinuation and increased fatal strokes and heart attacks (14).

Given that nocebo effects contribute to perceived side effects and may influence clinical outcomes and patients' adherence to medication we should consider how to avoid them in clinical trials and practices (15). For example, nocebo effects might be reduced by tailoring patient-clinician communication to balance truthful information about adverse events with expectations of outcome improvement, exploring patients' treatment beliefs and prior negative therapeutic history, and paying attention to framing (ie, treatment description) and contextual effects (ie, price). Through an understanding of the physiological mechanisms, strategies could be developed to reduce nocebo effects.

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Figure 1.
Medication price and labeling create expectancies of side effects that can lead to nocebo hyperalgesia that is in turn, mediated by an activation of the rACC-PAG-spinal cord coupling.