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Details:

(Form Updated: 08/11/2010)

WISCONSIN STATE LEGISLATURE ...
PUBLIC HEARING - COMMITTEE RECORDS

2009-10

(session year)

Senate

(Assembly, Senate or Joint)

Committee on ... Commerce, Utilities, Energy, & Rail (SC-CUER)

COMMITTEE NOTICES ...

- Committee Reports ... **CR**
- Executive Sessions ... **ES**
- Public Hearings ... **PH**

INFORMATION COLLECTED BY COMMITTEE FOR AND AGAINST PROPOSAL

- Appointments ... **Appt** (w/Record of Comm. Proceedings)
- Clearinghouse Rules ... **CRule** (w/Record of Comm. Proceedings)
- Hearing Records ... bills and resolutions (w/Record of Comm. Proceedings)
  - (**ab** = Assembly Bill) (**ar** = Assembly Resolution) (**ajr** = Assembly Joint Resolution)
  - (**sb** = Senate Bill) (**sr** = Senate Resolution) (**sjr** = Senate Joint Resolution)
- Miscellaneous ... **Misc**

* Contents organized for archiving by: Gigi Godwin (LRB) (August/2011)

Ledge Wind Economic Loss Analysis

These figures are simple calculations/rounded numbers and do not show every little nut & bolt of the project, but it sure opens one's eyes to the senseless option these mechanical dinosaurs really are.

The wind is free, using it to produce power is not!!

Income/turbine step #1

1.5 megawatt turbine (1500 kilowatts)
X 24 hours/day
X 20% efficiency
7200 kilowatts/day

The combined aggregate assessed values of Holland, Morrison, & Wrightstown is $387 million. Property values will drop 10-100%, depending upon proximity to a turbine. An average of 20% would equate to $77 million!

Turbines in our low wind production state are only 17-22% efficient. In the peak time of electrical consumption, turbines are at their worst/lowest output. We cannot rely on this output, so nuclear & coal still have to supply our requirements. (ref. WPS & We Energies websites) This 20% is confirmed by a retired WPS employee interview and was accepted as factual by an Invenergy spokesman in a local paper published on 3/27/10.

Income/turbine step #2

7200 kilowatts/day
X $.07/kilowatt
$500/day gross income
X 30 days/month
$15,000 *gross income/month*

Our local utility is paying $.07/kw to an owner of a local methane generator (a renewable energy source)

On our local electric bill we are charged about $.12/kilowatt, retail.

On a retail basis, these figures & other research sources show costs ranging from $.18-$.22 to produce a kilowatt from wind. This increases our electric rates 15-50%

Contract signers will receive an estimated $24 million over 30 years.

$666/mo
X12mo
X30 yrs
X100 turbines

Expense/turbine step #1

$3,200,000 turbine cost
@ 5% simple interest
30 years
$17,100/month amortized payment

Commonly publicized cost of Ledgewind Project 1.5 MGW turbines

Commonly publicized length of service for Ledgewind Project 1.5 MGW turbines

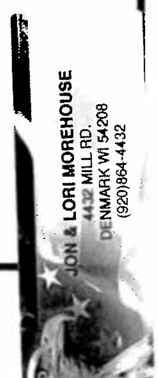
Invenergy literature states over $3,000,000/yr in maintenance for 100 turbines

Although confidential, based on the contracts that have been offered, as well as signed, a range of $8-$10,000/turbine/year was determined as payment to these land owners. ($8,000 was used here)

Expense/turbine step #2

Payment to contract signers……$666/month
Cost of maintenance…………$2,500/month
Cost to de-commission…………$900/month
Total misc. expenses…………$4,066/month

An employee in the wind equipment manufacturing industry stated that it cost $325,000 to PROPERLY take down a turbine, tower, & foundation. ($325,000 divided by 360 months)



Summary

$15,000 gross income/turbine/month
-$17,100/month amortized payment/turbine
-$4,066/month/turbine Total misc. expenses
-$6,166 *net loss//turbine/month*
X 12 months/year
-$74,000 *net loss/turbine/year*
X 30 year life of project
-$2,220,000 *net loss/turbine for 30 year life*
X 100 industrial turbines
-$222,000,000 *net loss of project over 30 years*

These dollars will come from increased electricity rates and off the backs of all of us as tax payers far into future generations as incentives & subsidies, up to $.20/ kw. It just puts us farther into debt and costs us our future!!! This is not "Green", it is ludicrous!!

Which turbine is closest to your home and is stealing your health, safety, & the value of your property??

bccrwe.org Giving up the Health-Safety-Aesthetics Property Values & Unity of our Community **bccrwe.org**

$$$$$$$PRICELESS$$$$$$$

We need transparency and to see the big picture of this project!!!! Every effort has been taken to use accurate numbers stated above based on research over the past months. Keep it simple, complete, & truthful. To date everything has been "confidential" & "non-disclosed" contractual information signed behind closed doors with land owners.

This information is not to be used for anything by anyone & is to be considered only as "informational".

Google united states wind resource maps

Search images Back to image results

See full size image

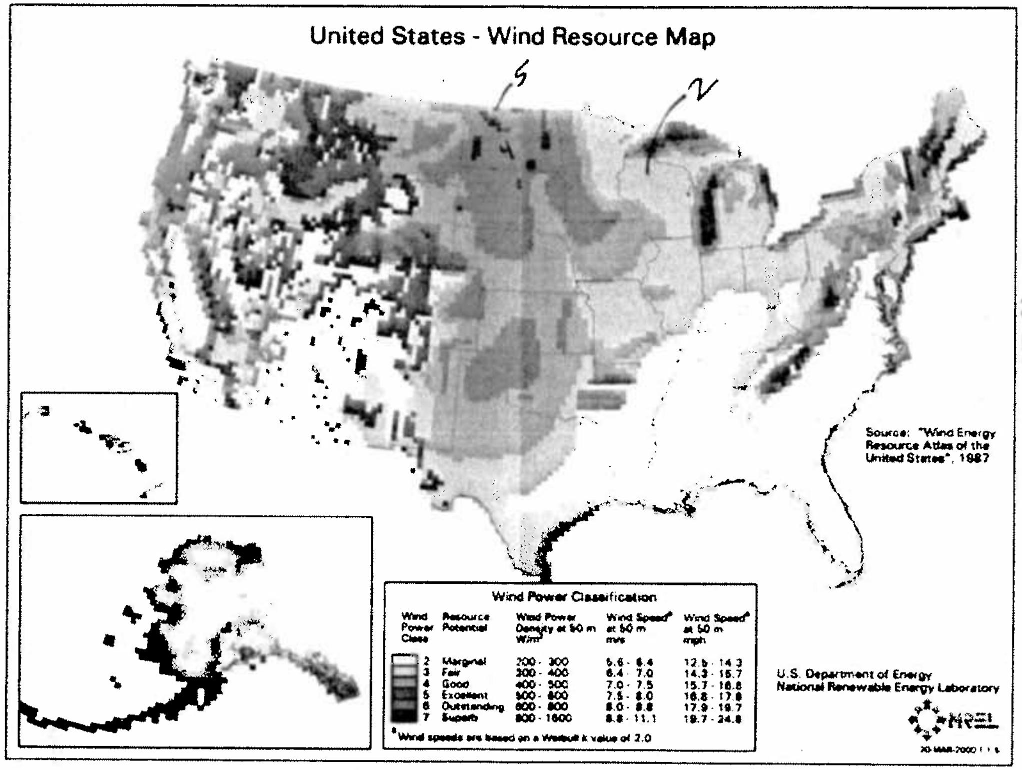
800 × 600 - 88k - gif - windeis.anl.gov/.../maps/images/wherewind800.gif

Image may be subject to copyright.

Below is the image at: windeis.anl.gov/guide/maps/map2.html

Remove frame [X]

U.S.A. Wind Resource Map

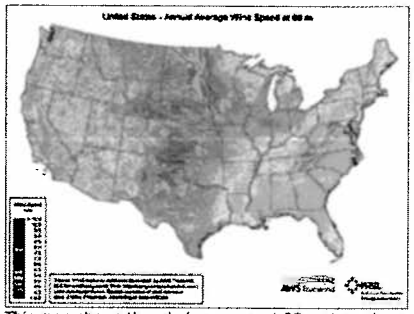


Wind energy resources in the United States

U.S. state maps of wind resources are available at: http://www.eere.energy.gov/windpoweringamerica/wpa/wind_maps.asp

National Renewable Energy Laboratory
Wind Research

Wind Resource Assessment


This map shows the wind resource at 80 meters above the ground for the contiguous United States.

All markets for wind turbines require an estimate of how much wind energy is available at potential development sites. Correct estimation of the energy available in the wind can make or break the economics of wind plant development. Wind maps developed from the late '70s to the early '90s provided reasonable estimates of areas in which good wind resources could be found. Now, new computing tools and new meteorological data sets allow researchers to create even more accurate and detailed wind maps of the world.

Wind mapping and validation techniques developed at the NWTC along with collaborations with U.S. companies produce high-resolution maps of the United States that paint a new picture of the wind resource potential. Information System mapping tools and an array of satellite, weather balloon, and meteorological tower data, combined with much-improved numerical computer models provide more data. The higher horizontal resolution of these maps allows for more accurate depiction of the overall wind resource and has led to the identification of new wind development areas where the wind resource was previously considered unsuitable.

NWTC provides technical assistance in wind resource assessment including the development and validation of high-resolution wind maps. The focus is to provide the wind industry, policy makers, and other stakeholders with applied wind resource data, information products (e.g., maps), and technical assistance with increasing emphasis on increased heights to effectively evaluate and develop wind potential. For example, a recent project resulted in the development of new wind resource maps at heights of 80 and 100 meters for the contiguous United States and estimates the wind energy potential that would be possible from development of the available windy land area.

- State Wind Maps
- International Wind Resource Maps
- Dynamic Maps, GIS Data and Analysis Tools

The ability to accurately predict when the wind will blow will help remove barriers to wind energy development by allowing wind-power-generating facilities to commit to power purchases in advance. NREL researchers work with federal, state, and private organizations to validate the nation's wind resources and support advances in wind forecasting techniques and dissemination. Wind resource validation is important for both wind resource assessment and the integration of wind farms into an energy grid. Validating new, high-resolution wind resource maps will provide an accurate reading of the wind resource at a particular site. Development of short-term (1 to 4 hours) forecasting tools will help energy producers proceed with new wind farm projects and avoid the penalties they must pay if they do not meet their hourly generation targets. In addition, validating new high-resolution wind resource maps will give people interested in developing wind energy projects greater confidence as to the level of wind resource for a particular site.

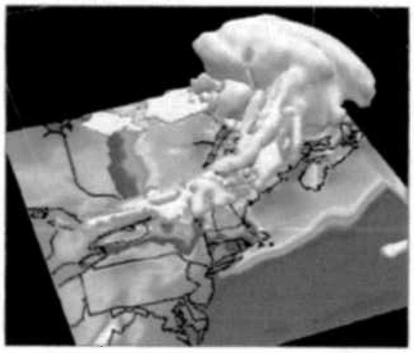
For more information about wind resource assessment and weather conditions, see:

- Wind Resource Assessment Handbook
- National Climatic Data Center Wind Speed Data
- NWTC Current Weather Conditions (Golden, CO)
- NWTC M2 Meteorological Tower information
- The National Center for Atmospheric Research
- The Weather Channel
- USA Today Weather

Due to the existence of military Special Use Airspace (SUA) (i.e., military airspace below 300 ft above ground level) used for military testing and training across the United States, Air Force wind consultants advise contacting them prior to applying for permits on all federal lands and nonfederal lands. As the Department of Defense lead for wind energy and SUA management, the Air Force will work to ensure that potential sites are mutually safe, secure, and efficient. Contact airforcewindconsult@pentagon.af.mil.

Wind Forecasting

The ability to accurately predict when the wind will blow will help remove barriers to wind energy development by allowing wind-power-generating facilities to commit to power purchases in advance. NREL researchers work with federal, state, and private organizations to develop model representations of the wind resource, including seasonal, daily, and hourly data, to better characterize the potential benefits and impacts of wind on system operation and assess transmission availability. The work will provide operators with a tool to anticipate wind generation levels and adjust the remainder of their generation units accordingly. Improved short-term wind production forecasts will let operators make better day-ahead market, operation, and unit-commitment decisions and help real-time operations in the hours ahead. Advanced forecasting systems will also help warn of extreme wind events so that operators can implement a defensive system posture if needed. The seamless integration of wind plant output forecasting—into both power market operations and utility control-room operations—is a critical next step in accommodating large penetrations of wind energy in power systems.



For more information about wind resource assessment and weather conditions, see:

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- NWTC Current Weather Conditions (Golden, CO)
- NWTC M2 Meteorological Tower information
- The National Center for Atmospheric Research

Table 1-1 Classes of wind power density at 10 m and 50 m[(a)].

Wind Power Class*	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m²)	Speed[(b)] m/s (mph)	Wind Power Density (W/m²)	Speed[(b)] m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m (5%/5000 ft) elevation.

*WEB NOTE: Each wind power class should span two power densities. For example, Wind Power Class = 3 represents the Wind Power Density range between 150 W/m² and 200 W/m². The offset cells in the first column attempt to illustrate this concept.

http://rredc.nrel.gov

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RIJKSUNIVERSITEIT GRONINGEN

120 pgs **DRAFT**

The sound of high winds:

the effect of atmospheric stability on wind turbine sound and microphone noise

Proefschrift
ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. F. Zwarts,
in het openbaar te verdedigen op
.........dag .... 20..
om .... uur

door
Godefridus Petrus van den Berg
geboren op 7 januari 1952
te Rotterdam

Promotores: prof dr ir H. Duifhuis
prof dr A.J.M. Schoot Uiterkamp

Beoordelingscommissie: prof dr ir H.P. Wit (University of Groningen)
prof dr V. Mellert (Carl von Ossietzky Universität Oldenburg)
prof dr ir G.A.M. van Kuik (Delft University of Technology)

ISBN:

Contents

I WIND POWER, SOCIETY, THIS BOOK: an introduction

This is the story of the discovery of a new phenomenon: why wind turbines sound different~~ly~~ at night time. ~~And, in this introduction, of~~Furthermore, we will see how -this ~~e impact of this~~ discovery can address ~~when the results involve~~ a problem in society, namely, that of perceived noise by residents living close to such turbines..
This introduction sketches the context in which my work proceeded~~ork, the topic of this book. is embedded~~: how the questions came up, why noise is an inseparable part of wind power development, a real physical phenomenon that exists apart from the attitudes either for or against. ~~that being critical does not need to imply a negative attitude.~~ Let's start at the beginning.

I.1 A 'new' phenomenon

The discovery was modest: I have not found a new law of nature or a new way to make money. It was rather the idea to apply old knowledge in a new context: the application of atmospheric physics to solve the mystery why people complained about noise from wind turbines that according to wind developers they should not even be able to hear. In principle it was not very difficult to find out why: when Walter Flight (a ~~very~~ Dutch citizen despite his name) told me he could see the wind turbines near his house rotating at high velocity while at the same time his garden was completely tranquil~~wind still~~, I thought: oh yes, I know that, that's because at night, especially on nice summer evenings, the atmosphere becomes~~turns~~ stable. I teach this in a course, Environmental Techniques. The phenomenon is treated extensively in this book, but for now it is sufficient to know that, due to strong winds at greater heights, coupled with very light winds at ground level (which implies a larger velocity gradient), wind turbines can appear to be a lot noisier in a night time atmosphere than they are in daytime.~~,~~ This ~~which~~ was why Walter and his neighbours complained. Also the nature of the ~~ir~~ sound changes: a thumping character can become very pronounced at night.

In this book I will often use the terms 'day' and 'night', though the distinction is more accurately stated as ~~precise~~ the atmosphere being unstable (which is usually in daytime, that is: sun up) or stable (night time, sun down). ~~In between~~There is another state, namely neutral, which has characteristics of both phenomena and which can occur in day as well as night time, but not very often in a temperate climate and over land~~onshore~~. Atmospheric stability means that vertical movements in the air are damped and as a consequence horizontal layers of air can have a greater difference in velocity: close to the ground the wind can be weak while higher up there is a strong wind.

Though in principle the explanation is simple and easily understood, it of course had to be solidly supplied with data~~argued~~ to ascertain that the explanation was correct. The first steps were extensive measurements in Bellingwolde, where severe complaints had arisen about noise from the nearby Rhede wind farm. This I did together with Richard de Graaf, then a physics student.

After thi~~s~~at simple discovery, a new mystery (to me) was why this did not play a role in the assessment of wind turbine noise?~~.~~ Every meteorologist knows about atmospheric stability, so why had none of the experts dealing with wind turbine sound ever come across it? Wind turbines have been built for several decades and since the 1980's in ever larger numbers, so

there should be a lot of accumulated experience. Had no one (except some residents) noticed the discrepancy between predicted and real noise exposure?
There are probably several reasons. One of them is that for a long time wind turbines were not big enough for the effects of atmospheric stability to be clearly noticeable. Since wind turbines have grown taller the effect manifests itself more clearly. Secondly, as the more distant locations have become scarce, more and more turbines are being built closer to where people live, so more people now experience the sound of wind turbines. Thirdly, atmospheric stability over flat land is easier to understand and quantify than in a mountainous or coastal area where the atmosphere is more complex so the effect on wind turbines may be less easily recognizable.

Wind turbines as such have not become that much noisier, despite their increase in height and blade~~wing~~ span (the sound power depends more on speed than on physical dimensions of the towers). Earlier machines could be quite noisy due to whining or severe thumping, and modern designs are certainly better. The point is they now reach into less familiar parts of the atmosphere.

Finally, an important reason to not recognize the unexpected high sound levels certainly is the fact that it impedes commercial interests and national policy. The positive ring of the term 'sustainability' helps investors in ~~sustainable~~ wind energy and local authorities (applying national policy) to counterbalance objections concerning possible disadvantages of new projects. As these objections are sometimes strong enough to torpedo projects, investors and authorities don't welcome more negative news. Though the population widely supports sustainable energy, reactions are less positive when a new project adversely affects their lives~~comes close~~. This 'contradictory behaviour' is in fact quite understandable: when a new project is planned in an area, residents for the first time have to balance the positive social consequences to the negative local impact: visual impact, flickering shadows and noise. In colder climates, ice throw from turbine blades has also become an issue.

The first reaction of wind energy proponents, represented by the Windkoepel ('Wind dome'), to our research results was to pay a consultant~~cy~~ to comment on our report [Van den Berg *et al* 2002]. This consultant~~cy~~ boasted of~~to~~ having~~e~~ advised ~~in~~ a large number of wind farm projects, so he clearly~~it~~ understood the position of the wind power industry. In the resulting 'second opinion' [Kerkers 2003] no material critique was presented, only procedural arguments were used to declare our results inaccurate and thus irrelevant. The Windkoepel issued a press report [Windkoepel 2003] concluding that we had made a lot of fuss, but had not contributed any new insights. They could get back to business.

I.2 Digging deeper

I too went back to my business, which can be summarized as~~:~~ helping citizen groups to defend their position by objective arguments using known principles of physics. In 2004 an article about my research was published in a scientific journal [Van den Berg 2004a] lending my results the~~more~~ respectability of peer review and triggering an international e-mail influx from interested consultants as well as worried residents, as our first report had done earlier on a national scale.

What still puzzled me at that time was how a single turbine could start thumping at night. I thought I understood how the modest blade swish of a single turbine could evolve into louder thumping: the small sound variations due to blade swish from several turbines could add up to louder pulses. But with a single turbine there is nothing to adds! Apart from this, in news media in the UK there were complaints that low frequency wind turbine noise had been underestimated and had been ~~could~~ making~~de~~ people sick.[1]

Some thoughts about this were presented at a conference in Maastricht [Van den Berg 2004b]. I agreed with delegate Jørgen Jakobsen, who presented a paper on low frequency wind turbine noise [Jakobsen 2004], that even though wind turbines did produce an appreciable amount of infrasound, the level was so far below the average human hearing threshold that it could not be a large scale problem. But it was possible that ~~perhaps~~ complaints had been ~~were~~ expressed in a way not understood by experts. Perhaps people bothered by the endless thumping of a relatively low pitched sound (such as I had heard myself on several occasions), thought that 'low frequency sound' was a~~the~~ term ~~slang~~ to use, as ~~a term they hoped was apparently more appropriate in~~ official sounding jargon. They might not be aware that the term 'low frequency sound' makes acousticians think of frequencies below 100 to 200 hertz, and in that range the sound level was not considered to be problematic. A classical misunderstanding perhaps, that could be clarified. After the Maastricht conference I wanted to quantify my ideas on the origin of the night time thumping of wind turbines and the relevance of low frequencies. This resulted in a second scientific article [Van den Berg 2005a] in which I tried to put these ideas ~~both things~~ together.

What had surprised me from early on was that people in the wind power business seemed to know so little about their raw material, the wind. In the Windkoepel press report [Windkoepel 2003] a wind turbine manufacturer's spokesman argued that if the hub height wind velocity indeed was structurally higher at night, this~~at~~ must be visible in production statistics. This indeed seems plausible, so why not investigate that? If the wind industry had done so, they might have come up with results I found from measured wind profiles at Cabauw over an entire year [Van den Berg 2005b]. Indeed for an 80 m high turbine the night time yield is significantly higher than expected, whereas the daytime yield is lower. The net result was that in the real atmosphere at Cabauw annual production was 14% to 20% (depending on wind turbine power settings) higher than in an atmosphere extrapolated from 10-m wind velocities with a perpetual neutral wind profile. For wind power production forecasting there is a method that incorporates a correction for atmospheric stability [Troen *et al* 1989], but such knowledge has never been used for sound exposure forecasting.

I.3 Commercial and policy implications

So from an energy point of view a stable atmosphere is very attractive. The challenge is to use that potential, but not put the burden on those living nearby. One solution is to build wind farms offshore where no people are affected if enough distance is kept (and calculation models are used that accurately model long range sound propagation over water). Over large bodies of water seasonal, not diurnal atmospheric stability will boost production in part of the year but lower it when the water has warmed. Another solution is to improve turbine design from two perspectives: decreasing sound power without substantially decreasing electric power, and reducing annoyance by minimizing fluctuations in the sound. Part of any solution

[1] Catherine Milner: "Wind farms 'make people sick who live up to a mile away'", online Telegraph, filed January 25, 2004 (Telegraph.co.uk, http://news.telegraph.co.uk/news/main.jhtml?xml=/news/2004/01/25/ nwind25.xml, consulted December 10, 2005)

is to respect complainants and try to achieve a better balance between national benefits and local costs.

Oblivious of any research, residents had already noticed a discrepancy between predicted and real noise exposure. Opponents of wind farms have organized themselves in recent years in the Netherlands and elsewhere, and word had spread that noise exposure in some cases was worse than predicted. Though atmospheric stability and sometimes a malfunctioning turbine could explain this, most wind farm developers and their consultants relied on the old prediction methods. An energy firm's spokesman complained that each and every new project attracted complaints (from local groups) and called this "a new Dutch disease".[1] This is a very narrow view on the problem, denying the detrimental effects for residents. If their real concerns are denied it is not unreasonable for residents to oppose a new project, because practical experience shows that once the wind farm is there (or any other noise producer) and problems do arise, complaints will very probably not alter the situation for ~~within~~ at least several years. Social scientists are familiar with such situations and suggest better strategies such as being honest and respectful, treating residents as equal partners, and not being arrogant: already in 1990 Wolsink mentioned this in a study on acceptance of wind energy and warned that it was wrong to label opposition as NIMBY (Not In My Back Yard) and refuse to recognize legitimate problems~~see the real worries~~ [Wolsink 1990]. It is sad that most ~~nevertheless part~~ of the proponents still emanate a WARAYDU attitude (We Are Right And You Don't Understand).

[1] NRC Handelsblad, August 26 2005: "Verzet tegen windmolens succesvol" ("Opposition to wind mills succesful")

When real complaints are not addressed seriously, the "new Dutch disease" may well become an Australian, British, Chinese or any nation's disease. In the Netherlands assessment of wind turbine noise still is according to the old standard procedure (with one exception, see chapter VII), assuming a neutral atmosphere at all times, even though this has been admitted to be wrong for more than a year now.[1] Consultants apparently are afraid to be critical, perhaps because they don't want to jeopardize new assignments or because a change in assessment implies they were not correct before (they were not correct, but we were wrong collectively). Though most consultants claim to be impartial, the problem of 'not biting the hand that feeds' is more subtle, as I concluded in an earlier desk study on the quality of acoustic reports [Van den Berg 2000]. *E.g.*, it involves authorities who do not question the position of paid experts, and a society hiding political decisions behind the demand for more research.

NOISE FROM WINDFARM MAKING LIFE A MISERY

A Recent settler in Caithness claimed yesterday his life is being blighted by ghostly noises from his new neighbours, the county's first large-scale windfarm. (.....) Mr Bellamy said: "The problem is particularly bad at night when I try to get to sleep and there's a strong wind coming from the direction of the turbines. "They just keep on droning on. It's a wooh wooh type of sound, a ghostly sort of noise. It's like torture and would drive anyone mad."
Mr Bellamy believes the noise is being transmitted through the ground since it seems to intensify when he lies down. He said he has got nowhere with complaints to the wind company and environmental health officers. "I feel I'm just getting fobbed off and can't get anyone to treat me seriously," he said.

Mr Bellamy has been asked to take noise readings every 10 minutes during problem times, something he claims is unrealistic to expect him to do. He said the company's project manager Stuart Quinton-Tulloch said they could not act until it had proof of unacceptable noise levels. Mr Bellamy said: "I'm not the moaning type and I have no problem with the look of the windmills. I'm not anti-windfarm. It's just the noise which is obviously not going to go away."
(.....)
Highland Council's principal environment officer Tom Foy who has been dealing with Mr Bellamy's complaint was unavailable for comment. His colleague David Proudfoot said he was aware of noise complaints about the Causewaymire turbines being lodged by two other residents, but said he had gone out several times and found no evidence to support the concerns.

Part of an article in *Press and Journal* of Aberdeen,25 May 2005

I hope other countries do not to follow the Dutch way: first denying the consistency and legitimacy of their complaints, then being late in addressing them and in the end finding this has created more opposition. It is evident that also in the UK there are (a few?) serious complaints from honest people that are not dealt with adequately. In at least some cases atmospheric stability

[1] In March 2004 I showed in an article in 'Geluid', a Dutch professional journal, how to deal with non-neutral atmospheric conditions within the existing legal procedures [Van den Berg 2004c]; in July 2004 the Ministry of Housing, Environment and Spatial Planning advised to investigate the 'wind climate' at new wind farm locations (letter on Beoordeling geluidmetingen Natuurkundewinkel RUG bij De Lethe, gem. Bellingwedde" to Parliament by State Secretary van Geel, June 21, 2004).

again seems to offer an explanation for observations of unpleasant wind turbine noise by residents (see example in box on previous page), but the matter has not been ~~is not~~ investigated correctly. I thought that this could perhaps be solved by the Sustainable Development Commission (SDC), the UK government's 'independent advisory body on sustainable development'. I wrote to the SDC about remarks on wind turbine noise in their report "Wind power in the UK" [SDC 2005], which was in my opinion too positive and somewhat overly optimistic regarding~~selective on~~ wind turbine noise. The SDC replied, on authority of its (unknown) consultants, that they had no detailed knowledge of atmospheric conditions in the UK but still thought an impulsive character of the noise 'likely to be very rare'. After I presented some examples the SDC preferred to close the discussion.

I.4 Wind turbines: large scale benefits and small scale impact

Though wind turbine noise is the main topic of this book, it is not the main problem in wind power development. Visual impact is the most important and most discussed local or regional effect. It is often presented as a matter of individual taste, though there are some common factors in 'public taste'. One such factor is the perceived contrast of a wind turbine (farm) and its environment: a higher contrast will have more impact, either in a positive or negative way. A peculiarity of turbines is that the rotational movement makes them more conspicuous and thus enhances visual impact. This common notion suggests that wind turbines in a built up area will have less impact relative to a remote natural area (though this may be overruled by the number of people perceiving the impact).

A second factor is attitude: *e.g.* farmers usually have a different attitude to the countryside than 'city folk' have, and hence they differ in judgments on the appropriateness of buildings, constructions and activities in the countryside. It is predictable that when residents have a positive association with a neighbouring wind farm they will experience less annoyance from the visual impact. For a wind turbine owner the sound of each blade passing means another half kWh is generated[1] and is perhaps associated with the sound of coins falling into his lap, a lullaby. The very same rhythm, like the proverbial leaking faucet tap, may prevent his opposing neighbour from falling asleep.

Other issues have gained attention in the public discussion, such as the modest contribution of wind energy to total energy consumption and the problematic variability of wind power. This is not the place to discuss these issues, except that they partially depend on a person's world view and expectations of the future. But I would like to show my personal position here. I find it astounding to realize that *all* wind turbine energy generated in the Netherlands in one year (2004) is equal to two months' *growth* of the total Dutch energy consumption. And even though wind turbine energy now provides about 2% of the total Dutch electricity consumption, this is only 0.2% of our total energy consumption.[2] This is also true on a global scale as is clear from figure I.1: wind power is now negligible and expected to supply 0.5% in 2030.

[1] when the turbine generates 2 MW at 20 rpm

[2] the percentages are based on data from Statistics Netherlands (Centraal Bureau voor Statistiek) for the Netherlands for the year 2004: wind energy production: 1.9 TWh; total electricity consumption: 108.5 TWh; total energy consumption: 919 TWh. Growth in total energy consumption in period 1995 – 2004: + 100 TWh or 1.7 TWh per two months. Growth in total electricity consumption 1995 - 2004: +23 TWh or 2.3 TWh per year.

Despite the disappointingly low percentages I still think that wind energy needs not be insignificant. In my view the problem is rather that we use such vast amounts of energy and keep on using ever more, which is a problem that no source, including wind power, can solve. Society will need to find a stand in the variety of opinions that have been brought forward since the 1970's. In a recent newspaper discussion about the liberalization of the energy market an opinion maker stated: "It is now generally appreciated th~~d~~at the end of the rich era of energy approaches rapidly, and the competition has begun for the last stocks", whilst his opponent the Minister or Economic Affairs wrote: "The lights must be kept burning, the gas must keep flowing".[1] I do not agree with the Minister: I think that a limited resource should require limited consumption, even at the cost of some discomfort to our spoiled society. If we can curb our Joule addiction, wind power may help us to produce part of the sustainable energy we need to satisfy basic needs.

Wind turbine noise is a problem that may grow due to neglect by~~of~~ wind energy proponents

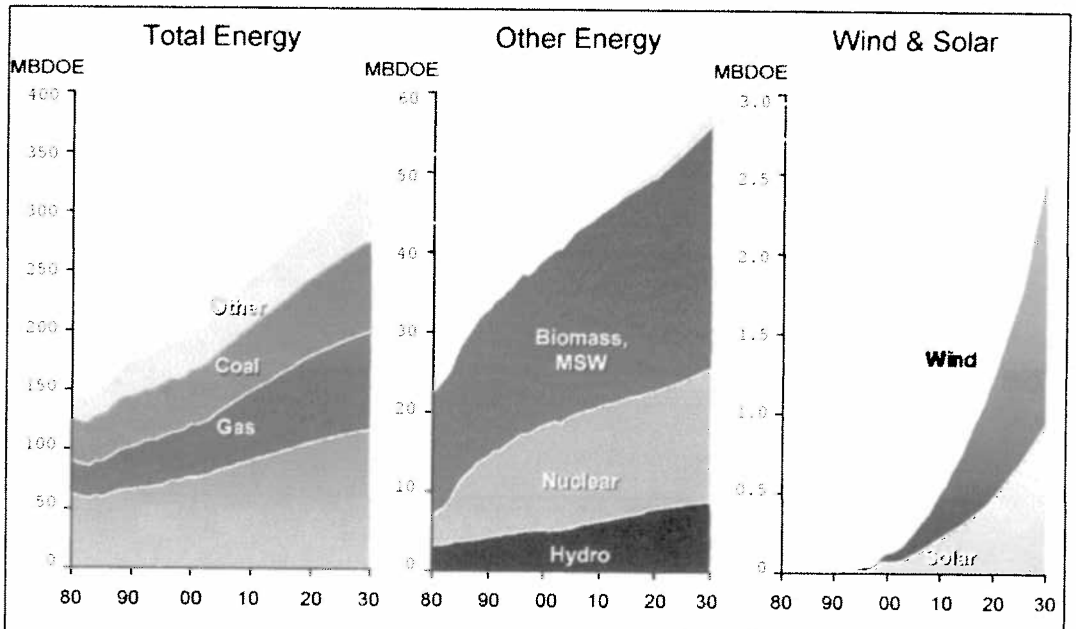

Figure I.1: history since 1980 and forecast until 2030 of global energy production according to ExxonMobil (adapted from their 2004 Energy Outlook); MBDOE = million barrels per day oil-equivalent = 620 TWh per year

and thus it may be another reason for part of the public, with politicians following, to turn away from wind power. This problem can be solved when it is also addressed~~sustainable~~ at the level of local impact. Some technical possibilities for noise reduction are given in this book and more hardware oriented ~~competent~~ people may ~~will~~ come up with better solutions. In addition to this, the social side of the problems must not be neglected. In a recent study [Van As *et al* 2005] it was concluded that "growing public resistance to onshore wind turbines" obstructs wind energy development in the Netherlands. According to the report this opposition is now the main bottle-neck: local communities and residents are faced with the disadvantages whilst others (proponents, society at large) reap the benefits. The report recommends that the former share in the benefits too.

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[1] NRC Handelsblad 8-11-2005, articles "Bezinning nodig over energiebeleid" ("Energy policy needs reflection") by Wouter van Dieren, and "Nieuw debat schept slechts onzekerheid" ("New debate only creates uncertainty") by Laurens Jan Brinkhorst; my translations

I.5 Microphone wind noise

In contrast to the impact my wind turbine research has had in society, the same knowledge of atmospheric physics helped me solve a non-controversial problem of interest to only a few: what is the nature of the noise that wind creates in a microphone? It occurred to me that if atmospheric turbulence was the cause, then one must be able to calculate the level of this noise. I was delighted when I found out how well theoretical considerations fitted hitherto only vaguely understood measurement results. Eureka!, such is the joy of work in science.

Somewhat unexpectedly this second discovery turns out to be~~o have a~~ related~~ion~~ to~~with~~ wind turbine sound, which is why it is in this book. Originally it was considered difficult to measure wind turbine sound, because ~~in~~ the strong winds that were supposed to cause high wind turbine sound levels, also were believed to be responsible for~~there was also~~ a lot of microphone wind noise. Solutions to this problem were either to put the microphone out of the wind on the ground or use several microphones and decrease microphone noise by averaging over all microphone signals. A new solution offered in this book is to take measurements in a stable atmosphere where near-ground wind velocity is so low that microphone noise is far less of a problem. One can measure sound at distances from a wind farm most researchers would not now believe to be possible.

The relationship is even stronger. In some countries the level of ambient background sound determines (part of) the limit imposed on sound exposure. To measure the level of this background sound the microphone must be put up in a place where residents stay outdoors, also in stronger winds. In this case it is important to discriminate between real ambient sound and the noise that wind produces in the microphone. With the calculation methods in this book it is now possible to do so.

I.6 Research aims

The issues raised above concerning~~about~~ wind turbine noise and its~~the~~ relationship ~~with~~to altitude dependent wind velocity led to the following issues to be investigated:

1- what is the influence of atmospheric stability on the speed and sound power of a wind turbine?
2- what is the influence of atmospheric stability on the character of wind turbine sound?
3- how widespread is the impact of stability on wind turbine performance: is it relevant for new wind turbine projects?; how can noise prediction take this into account?
4- what can be done to deal with the resultant ~~a possibly~~ higher impact of wind turbine sound?

Apart from these directly wind turbine related issues, a final aim was to address a measurement problem:

5- how does wind on a microphone affect the measurement of the ambient sound level?

I.7 Text outline and original work

This book gives an overview of results of the wind turbine noise research that has been ~~such as I have~~ presented in~~to~~ the international arena in the last few years, as well as some opinions on this topic in the Introduction and Epilogue. Most of the text in this book has been published in scientific journals or presented at conferences. The texts have however been adapted somewhat so as to form a continuous story without too much overlap. Other changes have been listed below.

- *Chapter II* is a reflection on some problems I encountered in doing research and presenting the results, most of it concerning wind turbine noise, but set against a more general background. It corresponds to a paper presented at Euronoise 2003 [Van den Berg 2003], but some overlap with later chapters is taken out and ~~a~~ new observations concerning the variation of wind turbine sound has been added (in II.2). The remaining text has been edited slightly.
- *Chapter III* gives some numbers on wind energy development in the European Union, as well as an introduction in the origins of aerodynamic wind turbine sound. It corresponds to the introductory sections of a published paper [Van den Berg 2005a] to which a remark on the spectrum of thickness sound (footnote in III.2) has been added. Also a description of sound and effects from a residential group with practical experience is added (in a box in section III.2).
- *Chapter IV* corresponds to my first paper on this topic [Van den Berg 2004a] on measurements at the Rhede wind farm. The section on Impulsive Sound has been taken out here and transferred to the next chapter. A new section (IV.10) has been added describing previously unpublished measurements at the Rhede wind farm as well as a comparison with calculated sound levels. Chapter IV demonstrates the fact that sound levels due to wind turbines have been systematically underestimated because hub height wind velocities were not correctly predicted. This effect is becoming more important for modern, tall wind turbines particularly~~and~~ when the atmosphere is 'non standard' (*i.e.* diverging from neutrality).
- In *chapter V* a second effect of atmospheric stability is investigated. Not only has the sound level been underestimated, but also the effect on the sound character: when the atmosphere turns stable, a more pronounced beating sound evolves. Most of the data are from the Rhede wind farm, complemented by data from a smaller single turbine elsewhere and theoretical calculations. In a section on the perception of fluctuating sound, it is explained how an apparently weak~~not very strong~~ sound level variation can indeed turn into~~a~~ audibly pronounced beating. This chapter corresponds to a published paper [Van den Berg 2005a], but the section on interaction of several turbines (V.2.4) has been combined with the corresponding section of the first paper [Van den Berg 2004a].
- In *chapter VI* data on atmospheric stability and wind statistics are presented. The raw data are from a location in the mid west of the Netherlands and have been provided by the KNMI. The analysis and application to a reference wind turbine help us to understand the behaviour of wind turbines and, together with research results from other countries, show that atmospheric conditions at the Rhede wind farm certainly were no exception. This chapter is the text of a paper presented at the WindTurbineNoise2005 conference [Van den Berg 2005b], with some results from that conference added (in section VI.6).
- In *chapter VII* some possibilities are discussed to cope with the effects of atmospheric stability on wind turbine noise, either by controlling wind turbine performance or by new designs. In part this is derived from a project in the town of Houten where the town council wants to permit a wind farm, taking into account the effect on residents, especially at night. This chapter is a somewhat expanded version (a concluding section has been added) of a second paper presented at the WindTurbineNoise2005 conference [Van den Berg 2005c].
- In *chapter VIII* a new topic is introduced: how does wind affect sound from a microphone? It shows~~proves~~ that atmospheric turbulence, closely related to -again-

atmospheric stability, is the main cause of wind induced microphone noise. The chapter corresponds to a published article [Van den Berg 2005d].

- In *Chapter IX* all results are summarized. Based on these general conclusions recommendations are given for a fresh look at wind turbine noise.
- Finally, in *chapter X*, some thoughts are given to conclude the text. After that the appendices give additional information.

II ACOUSTICAL PRACTICE AND SOUND RESEARCH

II.1. Checking compliance to limits

In 2001 the German wind park Rhede was put into operation just 400 m from the Dutch border. Local authorities as well as residents at the Dutch side had opposed the construction of the 17 wind turbines because of the effects on landscape and environment: with 98 m hub height the 1.8 MW turbines would dominate the skyline of the early 20th century village of Bellingwolde and introduce noise in the quiet area. With the turbines in operation residents at 500 m and more from the wind park found the noise (and intermittent or flicker shadow, which will not be dealt with here) worse than they had expected. The wind park operator declined to take measures as acoustic reports showed that German as well as Dutch noise limits were not exceeded. When the residents brought the case to a German court, they failed on procedural grounds. For a Dutch court they had to produce arguments that could only be provided by experts.

Science Shops are specifically intended to help non-profit groups by doing research on their behalf. For the Science Shop for Physics in Groningen noise problems constitute the majority of problems that citizens, as a group or individually, come up with. Although the aim of our research is the same as for acoustic consultants –to quantify sound levels relevant for annoyance- the customers are different: consultants mostly work for the party responsible for the sound production, whereas the Science Shop mostly works for the party that is affected by the sound. This may lead to different research questions. In the case of wind park Rhede a consultancy will check the sound production of the turbines and check compliance of the calculated sound immission level with relevant limits. The Science Shop however, taking the strong reaction from the residents as a starting point, wanted to check whether the real sound immission agrees with the calculated one and whether sound character could explain extra annoyance.

Earlier I showed in a Dutch magazine [Van den Berg 2000], on the basis of 30 acoustic reports, that acoustic consultants tend to rely too much on information from their customers, even when they had reason to be critical about it. As consultants' customers are usually noise producers and authorities, the point of view of those that are affected by noise is not usually very prominent. The present paper shows that for wind turbines a similar case can be made.

II.2 Results from our wind turbine research

The results of the investigation of the sound from the wind park Rhede are given in the next chapters. Here the results will be dealt with briefly. The main cause for the high sound level perceived by residents is the fact that wind velocities at night can, at 100 m height, be substantially higher than expected. As a consequence a wind turbine produces more sound. As measured immission levels near the wind park Rhede show, the discrepancy may be very large: sound levels are up to 15 dB (!) higher than expected at 400 m from the wind park. At a distance of 1500 m actual sound levels are 18 dB higher than expected, 15 dB of this because of the higher sound emission and 3 dB because sound attenuation is less than predicted by the sound propagation model. The important point is not so much that the maximum measured sound level is higher than the maximum expected sound level (it was, around +2 dB, but this was not an effect of the wind velocity profile). The point is that this maximum does not only occur at high wind velocities as expected, accompanied by high wind induced ambient sound levels, but already at relatively low wind velocities (4 m/s at 10 m height) when there is little wind at the surface and therefore little wind induced background sound. Thus, the discrepancy of 15 dB occurs at quiet nights, but yet with wind turbines at almost maximum power. This situation occurs quite frequently.

A second effect that adds to the sound annoyance is that the sound has an impulsive character. The primary factor for this appeared to be the well known swishing sound one hears close to a turbine. For a single turbine these 1 – 2 dB broad band sound pressure fluctuations would not classify as impulsive, but at night this swish may evolve into a less gentle thumping. Also, when several turbines operate nearly synchronously the pulses may occur in phase increasing pulse strength further. In the wind farm, close to a turbine, we never heard the impulsiveness. Indeed, close to a turbine it seems that most sound is coming from the downgoing blade, not when it passes the tower. One has to be careful in estimating blade position, as an observer at, say, 100 m from the foot of the tower is 140 m from a 100 m hub and therefore hears the sound from a blade approximately half a second after it was produced, in which time a blade may have rotated over some 30°. Recently Oerlemans [2005] explained this phenomenon: when the blade comes down and heads towards the observer, the observer is at an angle to the blade where most sound is radiated (see remark on directivity just below equation B.5 in Appendix B). On top of that the high tip velocity (70 m/s) causes a Doppler amplification. Both effects increase the sound level for our observer. This observation cannot however be used for a distant turbine as in that case the observer sees the rotor sideways. In that case the change due to the directivity of the sound is small, and also the Doppler effect is almost nil as the change in the velocity component towards the observer is very small.

II.3 Early warnings of noisy wind turbines?

One may wonder why the strong effect of the nightly wind profile or the pulselike sound was not noticed before. In the 1998 publication IEC 16400 again only the neutral logarithmic wind profile is used [IEC, 1998]. And even in 2002 a Dutch report stated in a general way that wind turbine sound is not impulsive [Kerkers *et al* 2002].
There have been some warnings. For example, in 1998 Rudolphi concluded from measurements that wind velocity at 10 m height is not a good measure for the sound level: at night the (58 m hub height) turbine sound level was 5 dB higher than expected [Rudolphi 1998]. Since several years residential groups in the Netherlands and abroad complained about annoying turbine sound at distances where they are not even expected to be able to hear the sound. Recently Pedersen *et al* [2003, 2004] found that annoyance was relatively high at (calculated) sound immission levels below 40 dB(A) where one would not expect strong annoyance.
As wind turbines become taller, the discrepancy between real and expected levels grows and as more tall wind turbines are constructed complaints may become more widespread. In the Netherlands residents near the German border were (apart from one single tall turbine elsewhere) the first Dutch to be acquainted with turbines of 100 m hub heights.

It may be that earlier discrepancies between real and projected sound immission were not sufficient to evoke strong community reactions and that only recently turbines have become so tall that the discrepancy now is intolerable.
There are other reasons that early warnings perhaps did not make much impression. One is that sound emission measurements are usually done in daytime. It is hard to imagine the sound would be very different at night time, so (almost) no one did. Until some years ago, I

myself could not imagine how people could hear wind turbines 2 km away when at 300 to 400 m distance the (calculated) immission level was, for a given wind velocity, already equal to the ambient background sound level (L_{95}). But it proved I had not listened in a relevant period: a stable night.
What is probably also a reason is the rather common attitude that 'there are always people complaining'. Complaints are a normal feature, not as such a reason to re-investigate. Indeed Dutch noise policy is not to prevent any noise annoyance, but to limit it to acceptable proportions. Added to this is a rather general conviction of Dutch authorities and consultants that routine noise assessment in compliance with legal standards must be correct. If measurements are performed it is to check actual emission levels –usually in normal working hours, so in daytime. It is quite unusual to compare the calculated sound immission from a wind turbine (park) with measured immission levels (so unusual that it is likely that we were the first to do so).
A third reason may be partiality to the outcome of the results. Wind turbine operators are not keen on spending money that may show that sound levels do not comply with legal standards. And if, as expected, they do comply, the money is effectively wasted. Apart from this, we have the experience that at least some organisations that advocate wind energy are not interested in finding out why residents oppose wind parks.

II.4 The use of standard procedures

Although our objective was to measure immission sound levels, we also wanted to understand what was going on: if levels were higher than expected, was that because emission was higher or attenuation less? Could there be focussing or interference? We therefore also measured sound emission as a function of rotational speed of the variable speed turbines. An interesting point that came up with the emission measurement was that compliance with the recommended standard [Ljunggren 1997 or IEC 1998] was impossible. As the park operator withdrew the co-operation that was previously promised, we had to measure emission levels with the full park in operation, as we obviously did not have the means to stop all turbines except the one to be measured, as the standard prescribes. To measure ambient background sound level, even the last turbine should be stopped.
In compliance with the standard the emission should be measured within 20% of the distance to the turbine equal to hub height + wing span. However, to prevent interference from the sound from other turbines the measurement location had to be chosen closer to the turbine. The primary check on the correctness of the distance (i.e. not too close to other turbines) was by listening: the closest turbine should be the dominant source. If not, no measurement was done, and usually a measurement near another turbine was possible. Afterwards we were able to perform a second check by comparing the measured sound immission of the wind park at a distance of 400 m with the level calculated with a sound propagation model with the measured emission level of all (identical) turbines as input. The calculated difference between a single turbine sound power level and the immission level was 58.0 dB (assuming a constant spectrum this is independent from the power level itself). The measured average difference was 57.9 dB, with a maximum deviation of individual measurement points of 1.0 dB. So our measurements proved to be quite accurate, deviating only 0.1 ± 1.0 dB from the expected value! In fact, from our measurements one may conclude that, to determine turbine sound power level, it is easier and cheaper to measure total sound emission at some distance from a wind park then measuring separate turbines. And in many nights the wind induced ambient sound, that easily spoils daytime measurements, is not an important disturbance!

Using a 1 m diameter round hard board, again to comply with the standard, was quite impractical and sometimes impossible. *E.g.* at one place potato plants would have to be cleared away, at another place one would have to create a flat area in clumps of grass in a nature reserve, both unnecessarily. Instead of the large board we used the side ($30 \cdot 44$ cm^2) of a plastic sound meter case. We convinced ourselves that (in this case) this was still a good procedure by comparing at one location sound levels measured on the case on soft ground with sound levels measured on a smooth tarmac road surface a few meters away, both at the same distance to the turbine as in the other measurements: there was no difference.

Whether a turbine produces impulsive sound is determined by listening to and measuring the sound near a single turbine (along with measurements to determine sound power and spectral distribution). In the Netherlands impulsivity is judged subjectively (by ear), not by a technical procedure as in Germany. Judgement can be supported with a sound registration showing the pulses. Interestingly, in Dutch practice only an acoustician's ear seems reliable, though even their opinions may disagree. From our measurements the impulsive character can be explained by the wind profile and the interaction of the sound of several turbines. Even at a time the impulsive character can be heard near residents' dwellings, it cannot clearly be heard close to the turbines in the wind park (as explained in section II.3). So here also there was need to do measurements where people are actually annoyed, and not to rely on source measurements only, certainly not from a single turbine.

When noise disputes are brought to court, it is clearly advantageous to have objective procedures and standards to assure that the technical quality, which can hardly be judged by non experts, is sufficient and therefore the results are reliable. In the case made here a standard may however be non-applicable for valid reasons. Nonetheless, the emission measurements have been contested on procedural grounds (*viz.* we have not complied to the standard [Kerkers 2003]), even though the immission sound levels were the primary research targets and we did not really need the sound emission measurement results (which, however, proved very accurate).

The tendency to put all noise assessment into technical standard procedures has the disadvantage that when there is a flaw in a legally enforced standard, still the standard is followed, not reality. It is hardly possible for non experts, such as residents, to bring other arguments to court. They, the annoyed, will have to hire an expert to objectify their annoyance. This is not something every citizen can afford.

II.5 Modelling versus measurements

Being able to calculate sound levels from physical models is a huge advantage over having to do measurements (if that, indeed, is possible) especially as in practical situations conditions keep changing and other sounds disturb the measurements. Because of its obvious advantages models have become far more important for noise assessment than measurements. In the Netherlands usually sound emission measurements are carried out close to a source to determine sound power levels. Then, with the sound power level, the immission level is calculated, usually on façades of residences close to the sound source. It is not common to measure immission levels in the Netherlands; in some cases (e.g. railway, aircraft noise) there is not even a measurement method (legally) available to check calculated levels.

A physical model however is never the same as reality. As was shown above, the widely used model for sound production from wind turbines is implicitly based on a specific wind profile.

This profile is not correct at night, although the night is the critical period for wind turbine noise assessment. Also attenuation with distance is overestimated for distances over 0,5 km. Even a perfect physical model will not reproduce reality if input values are not according to reality. An example is to apply sound power levels from new sources (cars, road surfaces, aeroplanes, mopeds, vacuum cleaners, etc.), maybe acquired in a specific test environment, to real life situations and conditions. In a wind farm south of the Rhede wind farm a turbine produced a clearly audible and measurable tonal sound, probably caused by a defect on a wing. It is very hard for residents to convince the operator and authorities of this annoying fact, partly because all experts say that modern wind turbines do not produce tonal sound. Incorrect models and incorrect input may well occur together and be difficult to separate. It should be important that calculation models are checked for correctness, also when they are used in new applications. Situations where (strong) complaints arise may indicate just those cases where models do not cover reality.

II.6 Conclusion

In modelling wind turbine sound very relevant atmospheric behaviour has been 'overlooked'. As a consequence, at low surface wind velocities such as often occur at night, wind turbine noise immission levels may be up to 15 or 18 dB higher than expected. The discrepancy between real and modelled noise levels is greater for tall wind turbines. International models used to assess wind turbine noise on dwellings should be revised for this atmospheric effect, at least by giving less attention to the 'standard' neutral atmosphere.

A discrepancy between noise forecasts and real noise perception, as a result of limited or even defective models, cannot always be avoided, even not in principle. Its consequences can however be minimised if immission levels are measured at relevant times and places. This relevancy is also determined by observations of those affected. It should always be possible to check noise forecasts by measurement.
For wind turbine noise (and other noise sources) standard measurement procedures require co-operation of the operator to be able to check emission sound levels. This introduces an element of partiality to the advantage of the noise producer. This is also generally a weak point in noise assessment: the source of information is usually the noise producer. There should always be a procedure to determine noise exposure independent of the noise producer.

Standard technical procedures have the benefit of providing quality assurance: when research has been conducted in compliance with a standard procedure lay persons should be able to rely on the results. It may however also have a distinct disadvantage for plain people opposing a noise source: when an assessment is not in agreement to a standard procedure is may not be accepted in court, regardless of the content of the claim. A negative side effect is the resulting dependency on legal as well as acoustical experts. If citizens are forced to use expert knowledge, one may argue that they should be given access to that knowledge. An important obstacle is the cost of that access.

III BASIC FACTS: wind power, the origins of modern wind turbine sound

III.1 Wind energy in the EU

Modern onshore wind turbines have peak electric power outputs around 2 MW and tower heights of 80 to 100 meters. In 2003, 75% of the global wind power peak electric output of 40 GW was installed in the European Union. The original European target for 2010 was 40 GW, but the European Wind Energy Association have already set a new target for 2010 of 75 GW, of which 10 GW is projected off-shore, while others have forecast a peak output of 120 GW for that year [EWEA 2004]. Whether this growth will actually occur is uncertain; with the proportional increase of wind energy in total electric power the difficulties and costs of integrating large scale windpower with respect to grid capacity and stability, reserve capacity and CO_2 emission reductions are becoming more prominent [see, *e.g.*, E.On 2004, ESB 2004]). However, further expansion of wind energy is to be expected, and as a result of this (predominantly on-shore) growth an increasing number of people may face the prospect of living near wind farms, and have reason to inquire and perhaps be worried about their environmental impact. Visual intrusion, intermittent reflections on the turbine blades, as well as intermittent shadows (caused when the rotating blades pass between the viewer and the sun), and sound, are usually considered potentially negative impacts.

III.2 Main sources of wind turbine sound

There are many publications on the nature and power of turbine sound: original studies [*e.g.* Lowson 1985, Grosveld 1985] and reviews [*e.g.* Hubbard *et al* 2004, Wagner *et al* 1996]. A short introduction on wind aeroacoustics will be given to elucidate the most important sound producing mechanisms.

If an air flow is smooth around a (streamlined) body, it will generate very little sound. For high velocities and/or over longer lengths the flow in the boundary layer between the body and the main flow becomes turbulent. The rapid turbulent velocity changes at the surface cause sound with frequencies related to the rate of the velocity changes. The turbulent boundary layer at the downstream end of an airfoil produces *trailing edge sound*, which is the dominant audible sound from modern turbines.

As is the case for aircraft wings, the air flow around a wind turbine blade generates lift. An air foil performs best when lift is maximised and drag (flow resistance) is minimised. Both are determined by the angle of attack: the angle (α) between the incoming flow and the blade chord (line between front and rear edge; see figure III.1). When the angle of attack increases from its optimal value the

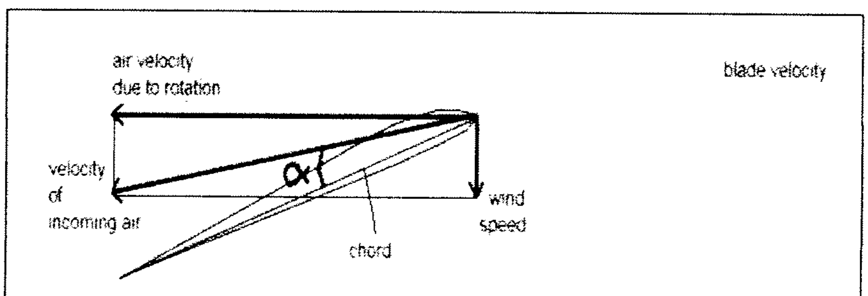


Figure III.1: flow impinging on a turbine blade

turbulent boundary layer on the suction (low pressure) side grows in thickness, thereby decreasing power performance and increasing sound level. For high angles of attack this eventually leads to stall, that is: a dramatic reduction in lift.
Apart from this turbulence inherent to an airfoil, the atmosphere itself is turbulent over a wide range of frequencies and sizes. Turbulence can be defined as changes over time and space in wind velocity and direction, resulting in velocity components normal to the airfoil varying with the turbulence frequency causing *in-flow turbulent sound.* Atmospheric turbulence energy has a maximum at a frequency that depends on height and on atmospheric stability. For wind turbine altitudes this peak frequency is of an order of magnitude of once per minute (0.017 Hz). The associated eddy (whirl) scale is of the order of magnitude of several hundreds of meters [Petersen *et al* 1998] in an unstable atmosphere, less in a stable atmosphere. Eddy size and turbulence strength decrease at higher frequency, and vanish due to viscous friction when they have reached a size of approximately one millimetre.
A third sound producing mechanism is the response of the blade to the change in lift when it passes the tower. The wind is slowed down by the tower which changes the angle of attack. The resulting sideways movement of the blade causes *thickness sound* at the blade passing frequency and its harmonics.[1] Thickness sound is also mentioned as sound originating from the (free) rotating blade pushing the air sideways. However, the associated air movement is relatively smooth and is not a relevant source of sound.

A more thorough review of these three sound production mechanisms is given in appendix B, where frequency ranges and sound levels are quantified in so far as relevant for the present paper. A modern wind turbine sound spectrum can now be divided in (overlapping) regions corresponding to these three mechanisms:

- Infrasound frequency ($f < 30$ Hz): the *thickness sound* is tonal, the spectrum containing peaks at the blade passing frequency f_B and its harmonics.
- Low frequency: *in-flow turbulent sound* is broad band noise with a maximum level of approximately 10 Hz and a slope of 3–6 dB per octave.
- High frequency: *trailing edge (TE) sound* is noise with a maximum level at 500–1000 Hz for the central octave band, decreasing with 11 dB for neighbouring octave bands and more for further octave bands.

Sound originating from the generator or the transmission gear has decreased in level in the past decades and has become irrelevant if considering annoyance for residents. As thickness sound is not relevant for direct perception, turbulent flow is the dominant cause of (audible) sound for modern wind turbines. It is broad band noise with no tonal components and only a little variation, known as blade swish. Trailing edge sound level is proportional to $50 \cdot \log M$ (see equation B.4 in appendix B), where M is the Mach number of the air impinging on the

[1] A thickness sound pulse has a length t_{pulse} with an order of magnitude of (tower diameter/tip speed ≈) 0,1 s, so its spectrum has a maximum at $1/t_{pulse} \approx 10$ Hz; the spectrum of a periodic series of Dirac pulses (unit energy 'spikes' with, here, a period of T_{blade}) is a series of spikes at frequencies n/T_{blade} ($n = 1, 2, 3, 4, ...$). When periodic thickness sound is considered as a convolution of the single pulse with a series of Dirac pulses, the Fourier transform is the product of the transforms of both, that is: the product of a pulse spectrum centered at $1/t_{pulse}$ and spikes at n/T_{blade}. The result is a series of spikes with the single pulse spectrum as an envelope, determining spike level. In practice $1/T_{pulse}$ usually has a value of 4 to 8 Hz (see *e.g.* [Wagner 1996]) and the harmonic closest to this frequency carries most energy.

blade. TE sound level therefore increases steeply with blade speed and is highest at the high velocity blade tips. Swish thus originates predominantly at the tips.
Sound from downwind rotors, *i.e.* with the rotor downwind from the tower, was considered problematic as it was perceived as a pulsating sound (see appendix B). For modern upwind rotors this variation in sound level is weaker. It is not thought to be relevant for annoyance and considered to become less pronounced with increasing distance due to loss of the effect of directivity, due to relatively high absorption at swish frequencies, and because of the increased masking effect of background noise [ETSU 1996]. However, an increase in the level of the swishing sound related to increasing atmospheric stability has not been taken into account as yet. In this context the periodic change in angle of attack near the tower proves to be important, not in relation to thickness sound but as a modulation period.

So, what's the sound like...?

(.....) Our experience is that mechanical noise is insignificant compared to the aerodynamic noise, or 'blade thump' as we call it. At "our" windfarm the mechanical noise is usually only audible when within about 100 metres of the turbine, but the blade thump can be heard at distances of up to 1.5 Km away.
(.....)
Some residents describe this noise as an old boot in a tumble dryer, others as a Whumph! Whumph! Whumph! Either way its not particularly loud at 1.5 km distance but closer than that and it can be extremely irritating when exposed to it for any period of time. Some residents have even resorted to stuffing chimney stacks with newspaper as the sound reverberates down the stack.
Because it is generally rhythmic, it's not the kind of noise that you can shut out of your mind, like, say, distant road noise - this is why we think the noise level stipulation on the planning conditions of such a windfarm development is woefully inadequate for protecting local residents from the noise effects of a windfarm.
All of us agree that the most disturbing aspect of the noise is the beat that we think is caused by the blades passing the tower of the turbine. As the rotational speed of the 3 bladed turbines is about 28 rpm "on full song" this results in a sound of about 84 beats per minute from each turbine.
The sound rises and falls in volume due to slight changes in wind direction but the end result for those in the affected area is a feeling of anxiety, and sometimes nausea, as the rate continually speeds and slows - we think that is maybe because this frequency of the pulses is close to the human heart rate and some residents feel that their own pulse rate is trying to match that of the turbines. (.....)

When does it strike?

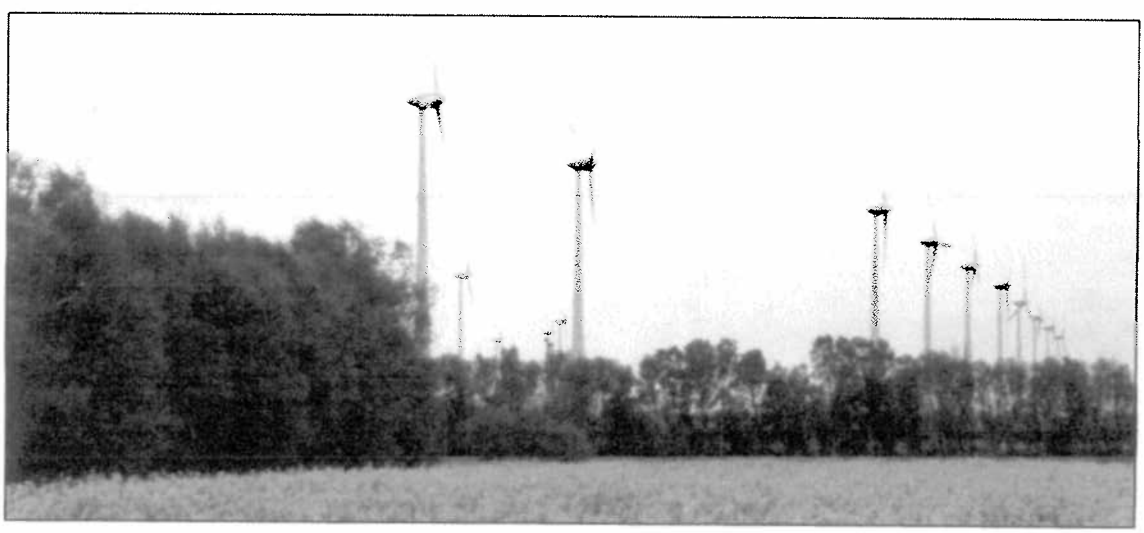
The windfarm makes a noise all the time it is operating, however there are times when it becomes less of a nuisance.
When the wind is very strong, the background noise created by the wind whistling around trees etc. drowns out the noise of the turbines and the problem is reduced. (.....)
In this area we all agree that the worst conditions are when the wind is blowing lightly and the background noise is minimal. Under these conditions residents up to 1 kilometre have complained to the Environmental Health department about the drone from the turbines. Unfortunately these are just the sort of weather conditions that you would wish to be outside enjoying your garden. (.....)
During the summer nights it is not possible for some residents, even as far away as 1000 metres, to sleep with the window open due to the blade thump. (......)

Excerpts describing wind turbine sound and its effects, from a page of the website of MAIWAG (consulted December 3, 2005), a group of residents in three villages in the south of Cumbria (UK)

IV LOUD SOUNDS IN WEAK WINDS: effect of the wind profile on turbine sound level

IV.1 The Rhede wind farrm

In Germany several wind turbine parks have been and are being established in sparsely populated areas near the Dutch border. One of these is the Rhede Wind Park in nortwestern Germany with seventeen 1.8 MW turbines of 98 m hub height and with 3-wing propellers of 35 m wing length. The turbines have a variable speed increasing with wind velocity, starting with 10 rpm (revolutions per minute) at a wind velocity of 2.5 m/s at hub height up to 22 rpm at wind velocities of 12 m/s and over.
At the Dutch side of the border is a residential area along the Oude Laan and Veendijk (see figure IV.1) in De Lethe: countryside dwellings surrounded by trees and agricultural fields. The dwelling nearest to the wind park is some 500 m west of the nearest wind turbine (nr. 16). According to a German noise assessment study a maximum immission level of 43 dB(A) was expected, 2 dB below the applied German noise limit. According to a Dutch consultancy immission levels would comply with Dutch (wind velocity dependent) noise limits.
After the park was put into operation residents made complaints about the noise, especially at (late) evening and night-time. The residents, united in a neighbourhood group, could not persuade the German operator into mitigation measures or an investigation of the noise problem and brought the case to court. The Science Shop for Physics had just released a report explaining a possible discrepancy between calculated and real sound immission levels of wind turbines because of changes in wind profile, and was asked to investigate the consequences of this discrepancy by sound measurements. Although at first the operator agreed to supply measurement data from the wind turbines (such as power output, rotation speed, axle direction), this was withdrawn after the measurements had started. All relevant data therefore had to be supplied or deduced from our own measurements.



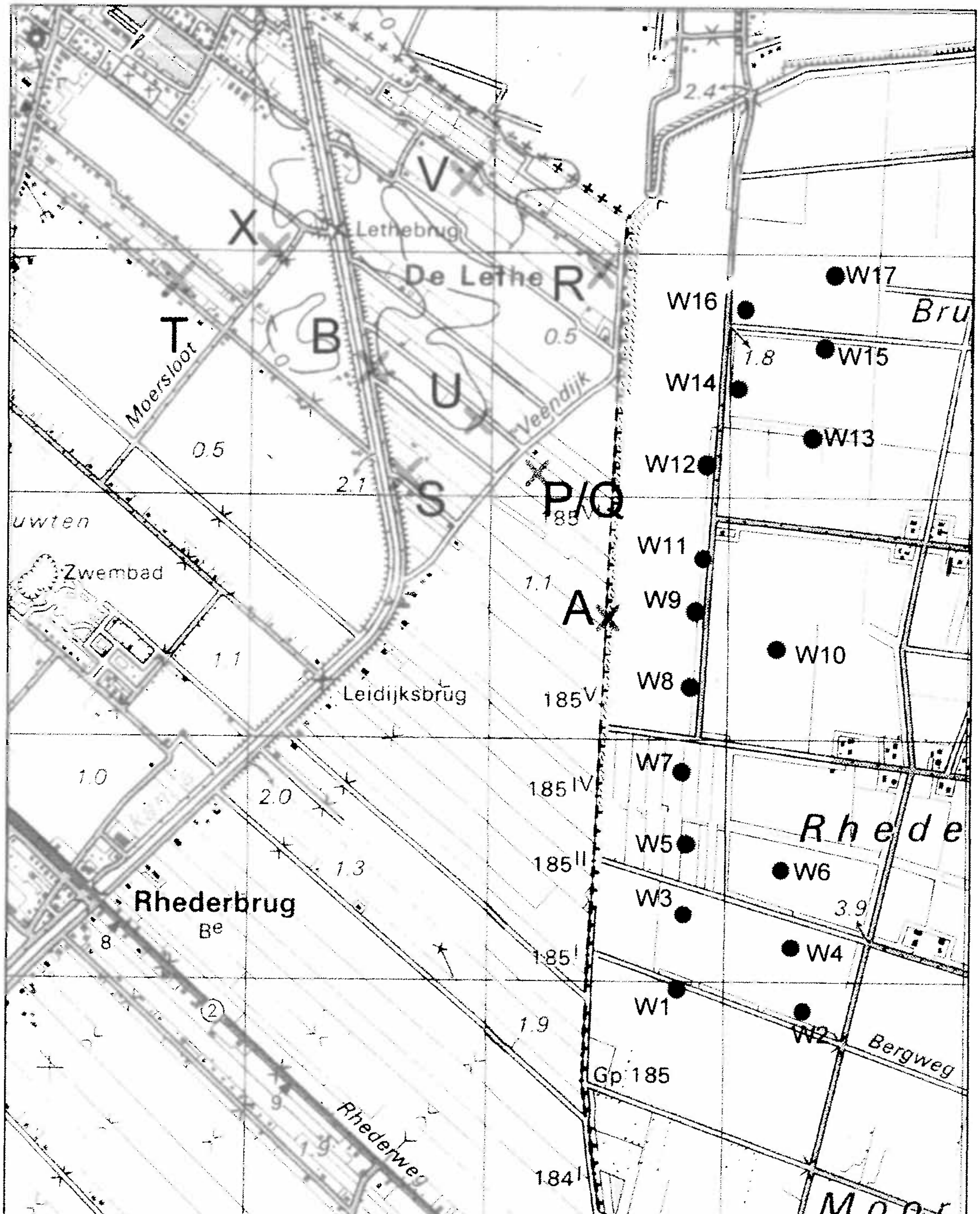


Figure IV.1: turbines (dots W1….W17) in and measurement locations (crosses A….X) near the Rhede wind farm; Duch – German border indicated by line of +++ (through A); section is 4 km x 5 km, north is at top

IV.2 Noise impact assessment

In the Netherlands and Germany noise impact on dwellings near a wind turbine or wind turbine park is calculated with a sound propagation model. Wind turbine sound power levels LW are used as input for the model, based on measured or estimated data. In Germany a single 'maximum' sound power level (at 95% of maximum electric power) is used to assess sound impact. In the Netherlands sound power levels related to wind velocities at 10 m height are used; the resulting sound immission levels are compared to wind velocity dependent noise limits. Implicitly this assessment is based on measurements in daytime and does not take into account atmospheric conditions affecting the wind profile, especially at night.

In the Netherlands a national calculation model is used [VROM 1999] to assess noise impact, as is the case in Germany [TA-Lärm 1998]. According to Kerkers [Kerkers 1999] there are, at least in the case of these wind turbines, no significant differences between both models.
In both sound propagation models the sound immission level L_{imm} at a specific observation point is a summation over j sound power octave band levels L_{Wj} of k sources (turbines), reduced with attenuation factors $D_{j,k}$:

$$L_{imm} = 10 \cdot \log [\Sigma_j \ \Sigma_k \ 10^{0.1 \cdot (LWj - Dj,k)}] \qquad (IV.1)$$

L_{Wj}, assumed identical for all k turbines, is a function of rotational speed. $D_{j,k}$ is the attenuation due to geometrical spreading (D_{geo}), air absorption (D_{air}) and ground absorption (D_{ground}): $D_{j,k} = D_{geo} + D_{air} + D_{ground}$.
Formula (IV.1) is valid for a downwind situation. For long term assessment purposes a meteorological correction factor is applied to (IV.1) to account for an 'average atmosphere'. When comparing calculated and measured sound immission levels in this study no such meteo-correction is applied.

IV.3 Wind turbine noise perception

There is a distinct audible difference between the night and daytime wind turbine sound at some distance from the turbines. On a summer's day in a moderate or even strong wind the turbines may only be heard within a few hundred meters and one might wonder why residents should complain of the sound produced by the wind park. However, in quiet nights the wind park can be heard at distances of up to several kilometers when the turbines rotate at high speed. In these nights, certainly at distances from 500 to 1000 m from the wind park, one can hear a low pitched thumping sound with a repetition rate of about once a second (coinciding with the frequency of wings passing a turbine mast), not unlike distant pile driving, superimposed on a constant broad band 'noisy' sound. A resident living at 1 km from the nearest turbine says it is the rhythmic character of the sound that attracks attention: beats are clearly audible for some time, then fade away to come back again a little later. A resident living at 2.3 km from the wind park describes the sound as 'an endless train'. In daytime these pulses are usually not audible and the sound fro the wind farm is less intrusive or even inaudible (especially in strong winds because of the then high ambient sound level).
In the wind farm the turbines are audible for most of the (day and night) time, but the thumping is not evident, although a 'swishing' sound –a regular variation in sound level caused by the pressure variation when a wing passes a turbine mast- is readily discernible. Sometimes a rumbling sound can be heard, but it is difficult to assign it, by ear, to a specific turbine or to assess it's direction.

IV.4 Stability dependent wind profiles

Wind velocity at altitude h_2 can be deduced from wind velocity at altitude h_1 with a simple power law function:

$$V_{h2}/V_{h1} = (h_2/h_1)^m \qquad \text{(IV.2)}$$

(1)

Equation IV.2 is an engineering formula used to express the degree of stability in a single number (the shear exponent m), but has no physical basis. The relation is suitable where h is at least several times the roughness length. Also, at high altitudes the wind profile will not follow (IV.2), as eventually a more or less constant wind velocity (the geostrophic wind) will be attained. At higher altitudes in a stable atmosphere there may be a *de*crease in wind velocity when a nocturnal 'jet' develops. The maximum in this jet is caused by a transfer of kinetic energy from the near-ground air that decouples from higher air masses as large, thermally induced eddies vanish because of ground cooling. In fact, reversal of the usual near-ground diurnal pattern of low wind velocities at night and higher wind velocities in daytime is a common phenomenon at higher altitudes over land in clear nights. Over large bodies of water atmospheric the phenomenon may be seasonal as stability occurs more often when the water is relatively cold (winter, spring). This may also be accompanied by a maximum in wind velocity at a higher altitude [Smedman *et al* 1996].

In flat terrain the stability exponent m has a value of 0.1 and more. In daytime or in windy nights ($0.1 < m < 0.2$) equation 1 does not deviate much from the logarithmic wind profile: for altitudes up to 100 m and low vegetation (roughness length < 10 cm). wind velocities calculated with equation 1 agree within 20% with the logarithmic wind profile.
For a neutral atmosphere, occurring under heavy clouding and/or in strong winds, m has a value of approx. 0.2. In an unstable atmosphere -occurring in daytime- thermal effects caused by ground heating are dominant. Then m has a lower value, down to approx. 0.1. In a stable atmosphere vertical movements are damped because of ground cooling. One would then eventually expect a parabolic wind profile, as is found in laminar flow, corresponding to a value of m of $0.7 = \sqrt{½}$. Our measurements near the Rhede wind farm (53° 6.2′ latitude, 7° 12.6′ longitude) at the German-Dutch border (see previous chapter) yielded values of m up to 0.6. A sample (averages over 0:00–0:30 GMT of each first night of the month in 1973) from data from a 200 m high tower in flat, agricultural land [Van Ulden *et al* 1976] shows that the theoretical value is indeed reached: in ten out of the twelve samples there was a temperature inversion in the lower 120 m, indicating atmospheric stability. In six samples the temperature increased with more than 1 °C from 10 to 120 m height and the exponent m (calculated from (1): $m = \log(v_{80}/v_{10})/\log(8)$) was 0.43, 0.44, 0.55, 0.58, 0.67 and 0.72. Comparable values have been estimated in the US Midwest and at a Spanish plateau. More data wil be presented in chapter V.

A physical model to calculate wind velocity V_h at height h is:

$$V_h = (u_*/\kappa)\cdot[\ln(h/z_o) - \Psi] \qquad \text{(IV.3)}$$

(2)

where $\kappa = 0.4$ is von Karman's constant, z_o is roughness height and u_* is friction velocity, defined by $u_*^2 = \sqrt{[(<uw>^2 + (<vw>^2]} = \tau/\rho$, where τ equals the momentum flux due to turbulent friction across a horizontal plane, ρ is air density and u, v and w are the time-varying components of in-wind, cross-wind and vertical wind velocity, with $<x>$ the time average of x. The stability function $\Psi = \Psi(\zeta)$ (with $\zeta = h/L$) corrects for atmospheric stability. Monin-Obukhov length L is an important length scale for stability and can be thought of as the height above which thermal turbulence dominates over friction turbulence; at heights below L (if L is a, not very large, positive length) is the stable boundary layer. The following approximations for Ψ, mentioned in many text books on atmospheric physics (*e.g.* [10]), are used:

- In a stable atmosphere ($L > 0$) $\Psi(\zeta) = -5\zeta < 0$.
- In a neutral atmosphere ($|L|$ large $\rightarrow 1/L \approx 0$) $\Psi(0) = 0$, and equation 2 reduces to a simple logarithmic expression.
- In an unstable atmosphere ($L < 0$) $\Psi(\zeta) = 2\cdot\ln[(1+x)/2] + \ln[(1+x^2)/2] - 2/\tan(x) + \pi/2 > 0$, where $x = (1-16\cdot\zeta)^{1/4}$.

For $\Psi = 0$ equation 2 reduces to $V_{h,log} = (u_*/\kappa)\cdot\ln(h/z_o)$, the widely used logarithmic wind profile. With this profile the ratio of wind velocities at two heights can be written as:

$$V_{h2,log}/V_{h1} = \log(h_2/z_o)/\log(h_1/z_o) \qquad \text{(IV.4)}$$

(3)

For a roughness length of $z_o = 2$ cm (pasture) and m = 0,14, the wind profiles according to equations IV.2 and IV.4 coincide within 2% for h < 100 m.
Formula IV.4 is an approximation of the wind profile in the turbulent boundary layer of a neutral atmosphere, when the air is mixed by turbulence resulting from friction with the surface of the earth. In daytime thermal turbulence is added, especially when there is strong insolation. At night-time a neutral atmosphere, characterized by the adiabatic temperature gradient, occurs under heavy clouding and/or at relatively high wind velocities. When there is some clear sky and in the absence of strong winds the atmosphere becomes stable because of radiative cooling of the surface: the wind profile changes and can no longer be adequately described by (IV.4). The effect of the change to a stable atmosphere is that, relative to a given wind velocity at 10 m height in daytime, at night there is a higher wind velocity at hub height and thus a higher turbine sound power level; also there is a lower wind velocity below 10 m and thus less wind-induced sound in vegetation.
With regard to wind *power* some attention is being paid to stability effects and thus to other wind profile models such as the diabatic wind velocity model (IV.3) [see, *e.g.*, Archer *et al* 2003, Baidya Roy *et al* 2004, Pérez *et al* 2004, Smedman *et al* 1996, Smith *et al* 2002].

Stability can also be categorized in Pasquill classes that depend on observations of wind velocity and cloud

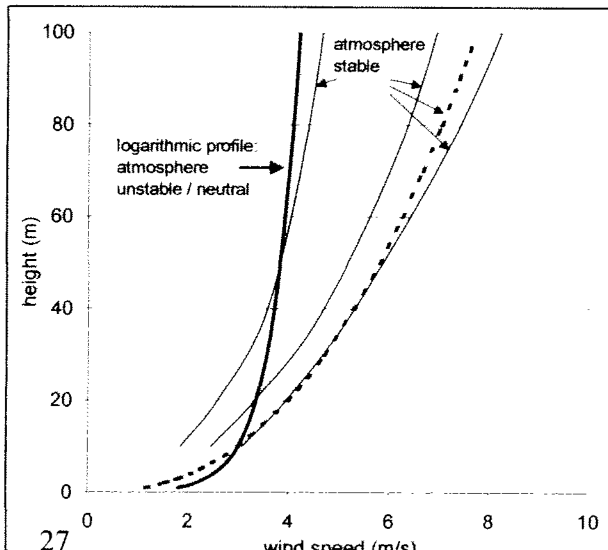


Figure IV.2: wind profiles

cover (see, *e.g.*, [LLNL 2004]). They are usually referred to as classes A (very unstable) through F (very stable). In a German guideline [TA-Luft 1986] a closely related classification is given (again closely related to the international Turner classification [Kühner]). An overview of stability classes with the appropriate value of m is given in table IV.1. In figure IV.2 wind profiles are given as measured by Holtslag [Holtslag 1984], as well as wind profiles according to formulae (IV.2) and (IV.4).

According to long-term data from Eelde and Leeuwarden [KNMI 1972], two meteorological measurement sites of the KNMI (Royal Netherlands Meteorological Institute) in the northern part of the Netherlands, a stable atmosphere (Pasquill classes E and F) at night occurs for a considerable proportion of night time: 34% and 32% respectively.

Table IV.1: stability classes and factor m

Pasquill class	name	comparable stability class [TA-Luft 1986]	m
A	very unstable	V	0.09
B	moderately unstable	IV	0.20
C	neutral	IV2	0.22
D	slightly stable	IV1	0.28
E	moderately stable	II	0.37
F	(very) stable	I	0.41

According to formula (IV.4) the ratio of wind velocities at hub height (98 m) and reference height, over land with low vegetation (z_o = 3 cm), would be $f_{log} = v_{98}/v_{10} = 1.4$. According to formula (IV.2) and table IV.1 this ratio would be 1.2 in a very unstable atmosphere and $f_{stable} = 2.5 = 1.8 \cdot f_{log}$ in a (very) stable atmosphere.

The fact that wind velocities at 10 m height may not be a good, unique predictor for hub height wind velocities has been put forward by Rudolphi [1998]. He concluded from measurements that wind velocity at 10 m height is not a good measure for wind turbine sound power: according to his measurements near a 58 m hub height wind turbine at night the turbine sound level was 5 dB higher than expected. This conclusion was not followed by more thorough investigation.
The question we have addressed is: what is the influence of the change in wind profile on the sound immission near (tall) wind turbines ?

IV.5 Measurement method

Sound immission measurements were made over 1435 hours, of which 417 hours at night. within four months on two consecutive locations with an unmanned Sound and Weather Measurement System (SWMS) consisting of a type 1 sound level meter with a microphone at 4.5 m height with a 9 cm diameter foam wind shield, and a wind meter at 10 m as well as at 2 m height. Every second wind velocity and wind direction (at 10 m and at 2 m height) and the A-weighted sound level were measured; the measured data are stored as statistical distributions over 5 minute intervals. From these distributions all necessary wind data and sound levels can be calculated, such as average wind velocity, median wind direction or equivalent sound level and any percentile (steps of 5%) wind velocity, wind direction or sound level, in intervals of 5 minutes or multiples thereof.

Also complementary measurements were done with logging type 1 and 2 sound level meters and a type 1 spectrum analyser to measure immission sound levels in the residential area over limited periods ([Van den Berg *et al* 2002], not reported here), and emission levels near the wind turbines. Emission levels were measured according to international standards [IEC 1998, Ljunggren 1997], but for practical purposes the method could not be adhered to in detail: with respect to the recommended values a smaller reflecting board was used for the microphone(30·44 cm2 instead of a 1 m diameter circular board) and a smaller distance to the turbine (equal to tower height instead of tower height + wing length); reasons for this are given in a separate paper [chapter II]. Also it was not possible to do emission measurements with only one turbine in operation.

IV.6 Results: sound emission

Emission levels Leq measured very close to the centre of a horizontal, flat board at a distance R from a turbine hub can be converted to a turbine sound power level LW [IEC 1998, Ljunggren 1997]:

$$L_W = L_{eq} - 6 + 10 \cdot \log(4\pi \cdot R^2) \qquad \text{(IV.5)}$$

From earlier measurements [Kerkers 1999] a wind velocity dependence of L_W was established as given in table IV.2. As explained above, the wind velocity at 10 m height was not considered a reliable single measure for the turbine sound power. Rotational speed is a better measure.

Emission levels have been measured, typically for 5 minutes per measurement, at nine turbines on seven different days with different wind conditions. The results are plotted in figure IV.3; the sound power level is plotted as a function of rotational speed N. N is proportional to wind velocity at hub height and could be determined by counting, typically during one minute, wings passing the turbine mast. This counting procedure is not very accurate (accuracy per measurement is ≤ 2 counts, corresponding to 2/3 rpm) and is probably the dominant reason for the spread in figure IV.3. The best logarithmic fit to the data points in figure IV.3 is:

$$L_W = 67.1 \cdot \log(N) + 15.4 \text{ dB(A)} \qquad \text{(IV.6)}$$

with a correlation coefficient of 0.98. The standard deviation of measurement values with respect to this fit is 1.0 dB.

Table IV.2: sound power level of wind turbines [Kerkers 1999]

Wind velocity v_{10}	m/s	5	6	7	8	9	10
sound power level L_W	dB(A)	94	96	98	101	102	103

Table IV.3: octave band spectra of wind turbines at L_W = 103 dB(A)

frequency	Hz	63	125	250	500	1000	2000	4000	L_W
this report	dB(A)	82	92	94	98	98	93	88	103
[Kerkers 1999]	dB(A)	85	91	95	98	98	92	83	103

At the specification extremes of 10 rpm and 22 rpm the (individual) wind turbine sound power level L_W is 82.8 dB(A) and 105.7 dB(A), respectively.
In table IV.3 earlier measurement results [Kerkers 1999] are given for the octave band sound power spectrum. Also in table IV.3 the results of this study are given: the logarithmic average of four different spectra at different rotational speeds. In all cases spectra are scaled, with formula (IV.6), to the same sound power level of 103 dB(A).
To calculate sound immission levels at a specific rotational speed (or vice versa) the sound power level given in formula (6), and the spectral form in table IV.3 ('this report') have been used.

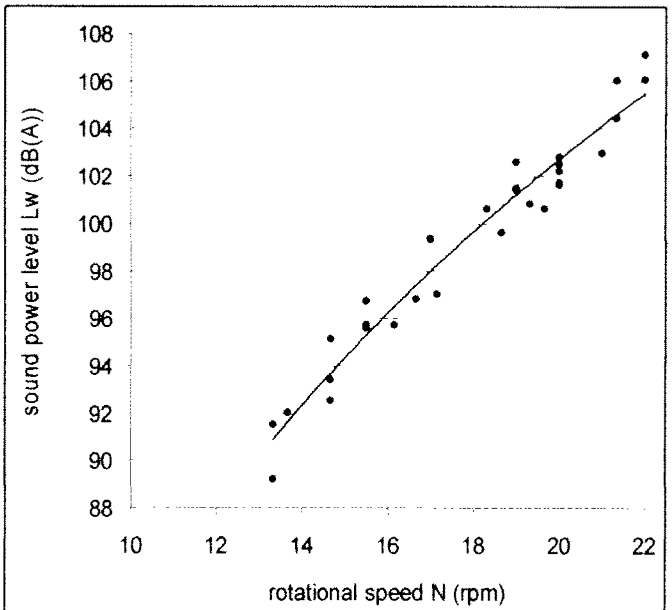


Figure IV.3: measured wind turbine sound power level L_W as a function of turbine rotational speed N

IV.7 Results: sound immission

The sound immission level has been measured with the unmanned SWMS on two locations. From May 13 until June 22, 2002 it was placed amidst open fields with barren earth and later low vegetation at 400 meters west of the westernmost row of wind turbines (location A, see figure IV.1). This site was a few meters west of the Dutch-German border, visible as a ditch and a 1.5 to 2 m high dike. From June 22 until September 13, 2002 the SWMS was placed on a lawn near a dwelling at 1500 m west of the westernmost row (location B), with low as well as tall trees in the vicinity. On both locations there were no reflections of turbine sound towards the microphone, except via the ground, and no objects (such as trees) between the turbines and the microphone. Apart from possible wind induced sound in vegetation relevant sound sources are traffic on rather quiet roads, agricultural activities, and birds. As, because of the trees, the correct (potential) wind velocity and direction could not be measured on location B, wind measurement data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A.

At times when the wind turbine sound is dominant, the sound level is relatively constant within 5 minute intervals. In figure IV.4 this is demonstrated for two nights. Thus measurement intervals with dominant turbine sound could be selected with a criterion based on a low variation in sound level: $L_5 - L_{95} \leq 4$ dB, where L_5 and L_{95} are the 5 and 95 percentile sound level. In a normal (Gaussian) distribution this would equal $\sigma \leq 1.2$ dB, with σ the standard deviation.

On location A, 400 m from the nearest turbine, the total measurement time was 371 hours. In 25% of this time the wind turbine sound was dominant, predominantly at night (72% of all 105 nightly hours) and hardly in daytime (4% of 191 hours). See table IV.4.

On location B, 1500 m from the nearest turbine, these percentages are almost halved, but still the turbine sound is dominant for over one third of the time at night (38% of 312 hours). The trend in percentages agree with complaints concerning mostly noise in the (late) evening and at night and their being more strongly expressed by residents closer to the wind park.

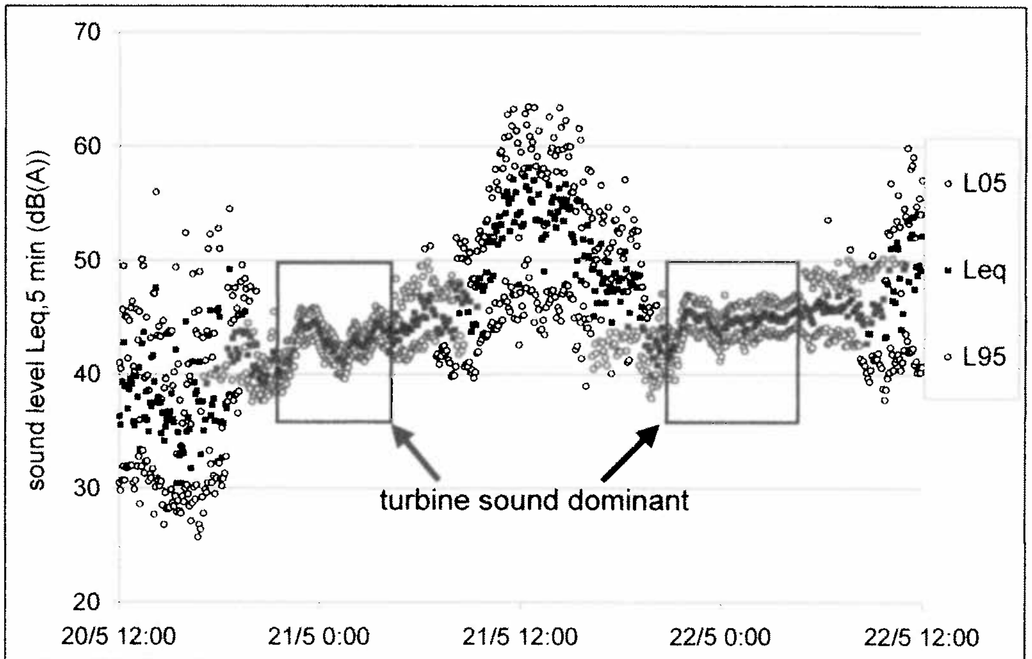


Figure IV.4: 48 hour registration of immission level (L_5, L_{eq} and L_{95}) per 5 minutes at location A; turbines are considered the dominant sound source if L_5-$L_{95} \leq 4$ dB

Table IV.4: total measurement time in hours and selected time with dominant wind turbine sound

Location	total time	Night 23:00-6:00	Evening 19:00-23:00	Day 6:00-19:00
A: total	371	105	75	191
A: selected	92 25%	76 72%	9 12%	7 4%
B: total	1064	312	183	569
B: selected	136 13%	119 38%	13 7%	4 0,7%

In figure IV.5 the selected (*i.e.* with dominant wind turbine sound) 5 minute equivalent immission sound levels $L_{eq,5\ min}$ are plotted as a function of wind direction (left) and of wind velocity (right) at 10 m height, for both location A (above) and B (below). It is not clear why the KNMI wind velocity data (used for location B) cluster around integer values of the wind velocity.

Also the wind velocity at 10 m and 2 m height on location A are plotted (in 5A and 5B, respectively), and the local wind velocity (influenced by trees) at 10 m on location B (5C). The immission level data points are separated in two classes where the atmosphere was stable or neutral, according to observations of wind velocity and cloud cover at Eelde. Eelde is the nearest KNMI site for these observations, but it is 40 km to the west, so not all observations will be valid for our area.

In figure IV.5B a grey line is plotted connecting calculated sound levels with sound power levels according to table 2 (the lowest value at 2,5 m/s is extrapolated [Van den Berg *et al* 2002]), implicitly assuming a fixed logarithmic wind profile according to formula (IV.2). If this line is compressed in the direction of the abscissa with a factor 2.6, the result is a (black) line coinciding with the maximum one hour values ($L_{eq,1\,h}$). Apparently the wind velocity is 2.6 times higher than expected. In figure IV.6 this is given in more detail: all 5 minute measurement periods that satisfied the L_5-L_{95}-criterion, with at least 4 periods per hour, were taken together in consecutive hourly periods and the resulting $L_{eq,T}$ (T = 20 to 60 minutes) was calculated. These 83 L_{eq}-values are plotted against the average wind velocity v_{10} over the same time T. Also plotted in figure IV.6 are: the expected immission levels calculated from (IV.1), implicitly assuming a logarithmic wind profile according to (IV.4), so f_{log} = 1.4; the immission levels assuming a stable wind profile (4) with m = 0.41, so f_{stable} = 2.5 = 1.8·f_{log}; the maximum immission levels assuming f_{max} = 3.7 = 2.6·f_{log}, in agreement with a wind profile

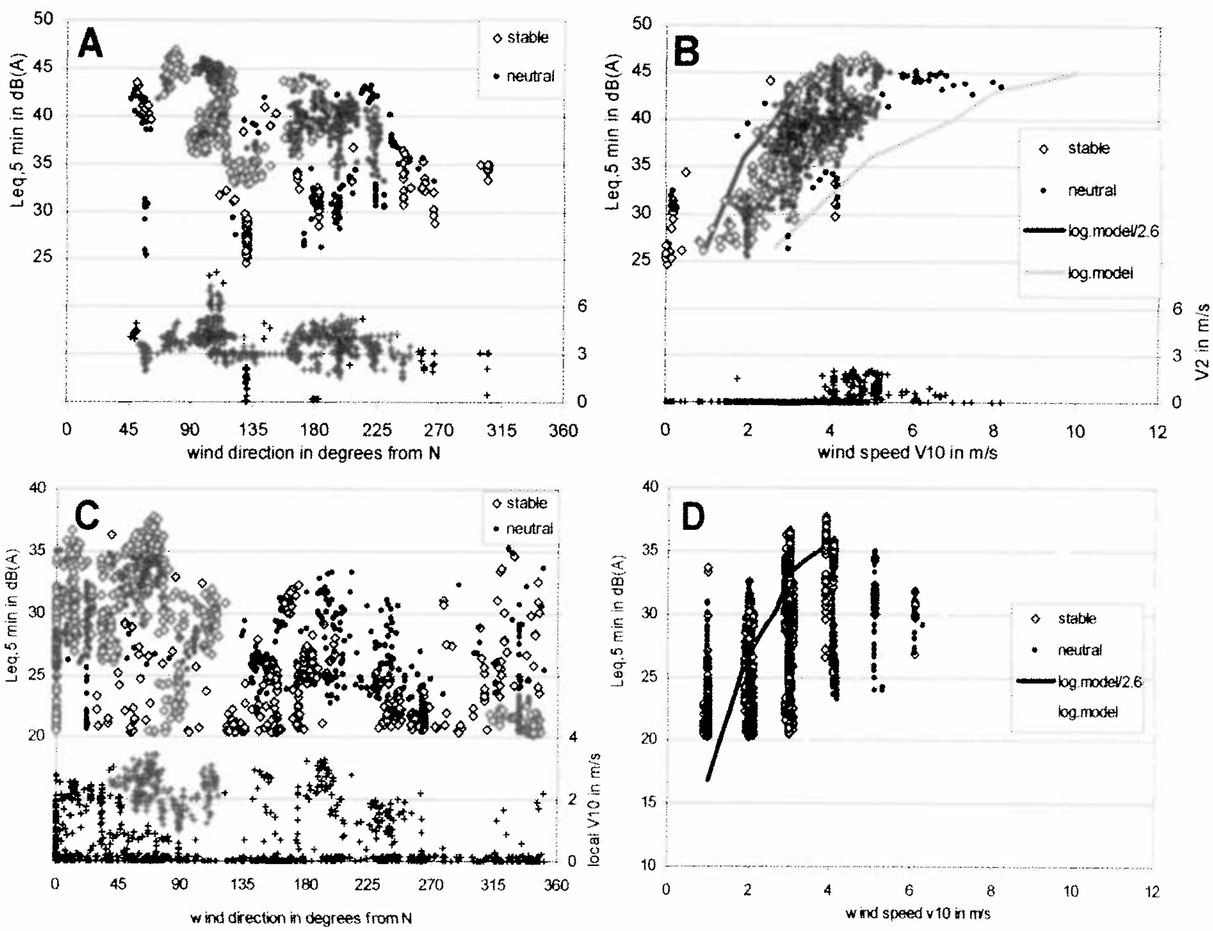


Figure IV. 5: measured sound levels $L_{eq,5\,min}$ at locations A (above) and B (below) as a function of median wind direction (left) and average wind speed (right) at reference height (10 m), separated in classes where the atmosphere at Eelde was observed as stable (open diamonds) or neutral (black dots). Also plotted are expected sound levels according to logarithmic wind profile and wind speed at reference height (grey lines in B and D), and at a 2.6 higher wind speed (black lines in B and D). Figures A, B and C also contain the wind speed v_{10}(A), v_2 (B), and the local v_{10} (C) disturbed by trees, respectively.

(IV.2) with m = 0.57. The best fit of all data points ($L_{eq,T}$) with $1 < v_{10} < 5.5$ m/s in figure IV.6 is $L_{eq} = 32 \cdot \log(v_{10}) + 22$ dB (correlation coefficient 0.80) agrees within 0.5 dB with the expected level according to the stable wind profile. The best fit of all 5 minute data-points in figure IV.5B yields the same result.

Thus on location A the highest one hour averaged wind velocities at night are 2.6 times the expected values according to the logarithmic wind profile in formula (IV.4). As a consequence, sound levels at (in night-time) frequently occurring wind velocities of 3 and 4 m/s are 15 dB higher than expected, 15 dB being the vertical distance between the expected and highest one-hour immission levels at 3- 4 m/s (upper and lower lines in figures 5B and 6). The same lines as in 5B, but valid for location B, are plotted in figure IV.5D; immission levels here exceed the calculated levels, even if calculated on the basis of a 2.6 higher wind velocity at hub height. This is the result of shortcomings of the calculation model for long distances, at least for night conditions: from the long term measurements at location B and short term (one night) at other locations ([12], not reproduced here) it follows that calculated sound immission levels, calculated according to the standard model used in the Netherlands [VROM 1999], underestimate measured levels at night with ca. 1 dB at distances of 550 – 1000 m increasing to ca. 3 dB at distances up to 1900 m.

As is clear from the wind velocity at 2 m height plotted in figure IV.5B, there is only a very light wind near the ground even when the turbines rotate at high power. This implies that in a quiet area with low vegetation the ambient sound level may be very low. The contrast between the turbine sound and the ambient sound is therefore at night higher than in daytime.

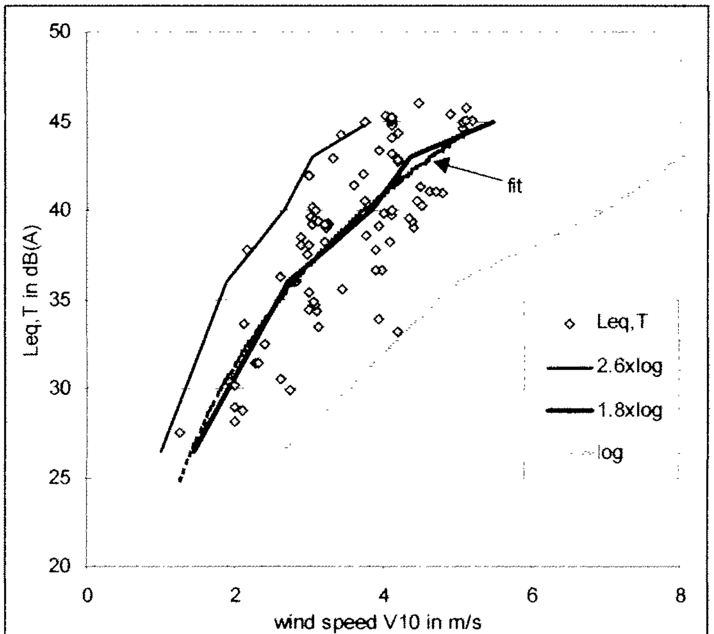


Figure IV.6: measured sound levels $L_{eq,T}$ (T = 20 - 60 min) at location A with best fit; and expected sound levels according to a logarithmic wind profile ($v_{98}/v_{10} = f_{log} = 1.4$), a stable wind profile ($v_{98}/v_{10} = 1.8 \cdot f_{log}$) and maximum wind speed ratio ($v_{98}/v_{10} = 2.6 \cdot f_{log}$).

Although at most times the wind turbine sound dominates the sound levels in figure IV.5, it is possible that at low sound levels, *i.e.* at low rotational speeds and low wind velocities, the L_5-L_{95}-criterion is met while the sound level is not entirely determined by the wind turbines. This is certainly the case at levels close to 20 dB(A), the sound level meter noise floor.

The long term night-time ambient background level, expressed as the 95-percentile (L_{95}) of all measured night-time sound levels on location B, was 23 dB(A) at 3 m/s (v_{10}) and increasing with 3.3 dB/m·s^{-1} up to $v_{10} = 8$ m/s [Van den Berg *et al* 2002]. Comparing this predominantly non-turbine background level with the sound levels in figure IV.5B and 5D, it is clear that the lowest sound levels may not be determined by the wind turbines, but by other ambient sounds (and instrument noise). This wind velocity dependent, non-turbine background sound level

L_{95} is, however, insignificant with respect to the highest measured levels. Thus, the high sound levels do not include a significant amount of ambient sound not coming from the wind turbines. This has also been verified in a number of evenings and nights by personal observation.

IV.8 Comparison of emission and immission sound levels

From the 30 measurements of the equivalent sound level $L_{eq,T}$ (with T typically 5 minutes) measured at distance R from the turbine hub (R typically 100√2 m), a relation between sound power level L_W and rotational speed N of a turbine could be determined: see formula (IV.6). This relation can be compared with the measured immission sound level $L_{i,T}$ (T = 5 minutes) at location A, 400 m from the wind park (closest turbine), in 22 cases where the rotational speed was known. The best logarithmic fit for the data points of the immission sound level L_{imm} as a function of rotational speed N is:

$$L_{imm} = 57.6 \cdot \log(N) - 30.6 \text{ dB(A)} \qquad \text{(IV.7)}$$

with a correlation coefficient of 0.92 and a standard deviation of 1.5 dB. Both relations from formulae (IV.6) and (IV.7) and the datapoints are given in figure IV.7. The difference between both relations is $L_W - L_{imm} = 9.5 \cdot \log(N) + 46.0$ dB. For the range 14 – 20 rpm, where both series have data points, the average difference is 57.9 dB, the maximum deviation from this average is 0.8 dB (14 rpm: 57.1 dB(A); 20 rpm: 58.6 dB(A); see lower part of figure IV.7). It can be shown by calculation that about half of this deviation can be explained by the variation of sound power spectrum with increasing speed N.

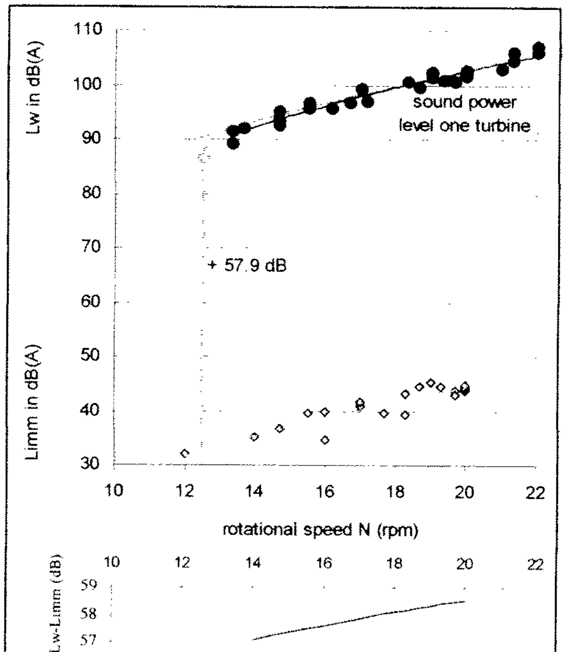


Figure IV.7: turbine sound power levels L_W measured near wind turbines and immission levels L_{imm} measured at 400 m from wind park: averages differ 57.9 dB; (below) increase of difference $L_W - L_{imm}$ with rotational speed

The sound immission level can be calculated with formula (IV.1). For location A, assuming all turbines have the same sound power L_W, this leads to $L_W - L_{imm} = 58.0$ dB. This is independent of sound power level or rotational speed, as it is calculated with a constant spectrum averaged over several turbine conditions, *i.e* speeds. The measured difference (57.9 dB) matches very closely the calculated difference (58.0 dB).

The variation in sound immission level at a specific wind velocity v_{10} in figures IV.5B and IV.5D is thus seen to correspond to a variation in rotational speed N, which in turn is related to a variation in wind velocity at hub height, not to a variation in v_{10}. At location A, N can be calculated from the measured immission level with the help of formula (IV.7) or its inverse form: $N = 3.4 \cdot 10^{L_{imm}/57.6}$.

IV.9 Effect of atmospheric stability

In figure IV.5 measurement data have been separated in two sets according to atmospheric stability in Pasquill classes, supplied by KNMI from their measurement site Eelde, 40 km to the west of our measurement site. Although the degree of stability will not always be the same for Eelde and our measurement location, the locations will correlate to a high degree in view of the relatively small distance between them. For night-time conditions 'stable' refers to Pasquill classes E and F (lightly to very stable) and corresponds to $V_{10} \leq 5$ m/s and cloud coverage $C \leq 50\%$ or $V_{10} \leq 3.5$ m/s and $C \leq 75\%$, 'neutral' (class D) corresponding to all other situations. Although from figure IV.5 it is clear that the very highest sound levels at an easterly wind ($\approx 80°$) do indeed occur in stable conditions, it is also clear that in neutral conditions too the sound level is higher than expected for most of the time, the expected values corresponding to the grey lines in figures IV.5B and D, derived from daytime conditions. According to this study the sound production, and thus wind velocity at 100 m height is at night often higher than expected, in a stable, but also in a neutral atmosphere. On the other hand, even in stable conditions sound levels may be lower than expected (i.e. below the grey lines), although this occurs rarely. It may be concluded from these measurements that a logarithmic wind profile based only on surface roughness does not apply to the night-time atmosphere in our measurements, not in a stable atmosphere and not always in a neutral atmosphere.

IV.10 Additional measurements

In several nights in the period that the SMWS was measuring at location A or B, manual measurements were performed at a number of locations in the area between 0.6 and 2.3 km west of the wind farm. The locations are plotted in figure IV.1. Most locations were close to dwellings, but two (locations U and X) were in open fields. Locations P and Q are close and at the same distance from the western row of turbines and can be considered equal with respect to the turbines (Q was chosen instead of P as P was at the verge of a garden with a loud bird chorus in the early morning). The surface of most of the area is covered with grass and low crops, with trees at some places.

For these measurements one or more logging sound level meters (01dB type SLS95 or SIP95, accuracy type 1 or 2) were used simultaneously, taking a broad band A-weighted sound pressure level every second. Before and after measurement the meters were calibrated with a 94.0 dB, 1000 Hz calibration source, and as a result measurement accuracy due to the instruments are within 0.2 dB. On every location the microphone was in a 10 cm spherical foam wind screen approximately 1.2 m above the surface. There were no reflections of the wind turbine sound to the microphone, except via the ground.

IV.10.1 Measured and calculated immission sound levels

Figure IV.8 gives a simultaneous registration from just before midnight on May 17, 2002, till noon on May 18, of the equivalent sound pressure levels per 5 minutes at locations A (from the SWMS), P/Q and U (from the manual meters) at distances to the westernmost row of turbines of 400, 750 and 1050 m, respectively. In the night hours the sound of the turbines was dominant at each of these locations, apart from an occasional bird or car. Also plotted in figure IV.8 are the wind velocity at 2 and 10 m heights at location A. The advantage of taking the sound level at A as a reference value is that it is not necessary to know the exact sound power level of the turbines themselves.

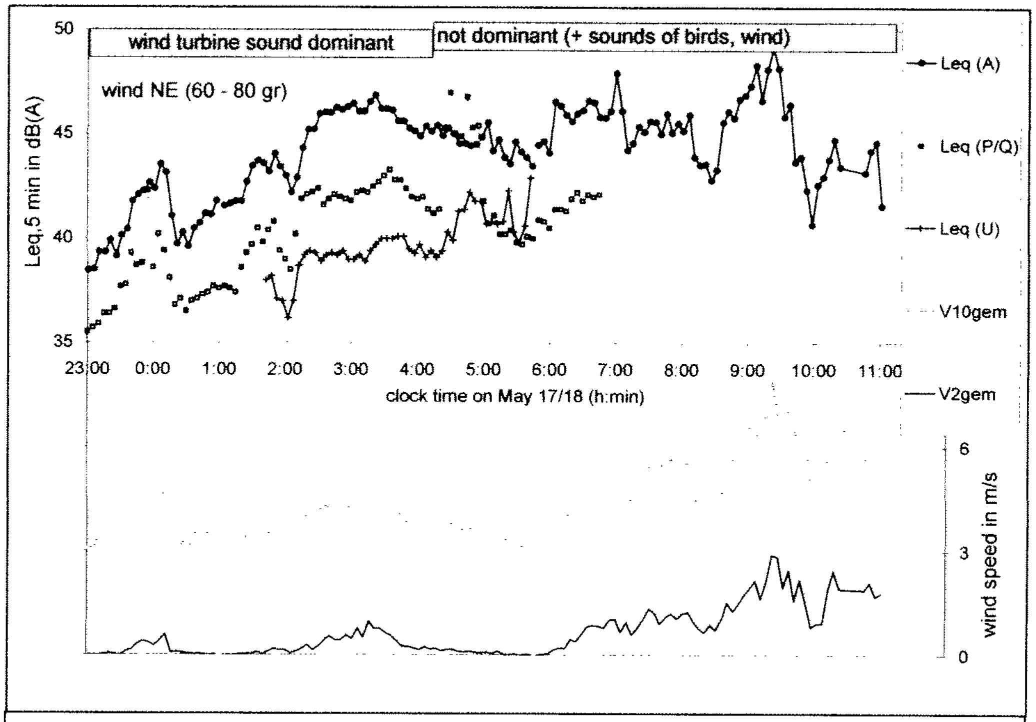


Figure IV.8: measured sound immission level ($L_{eq,5mn}$) at locations A, P/Q, and U, and wind velocities at A with an eastnortheasterly wind

A short change in wind velocity just after 2:00 AM is apparently accompanied by a similar hub height change, as the sound level varies much in the same way. However, the registrations show that the sound level increases steadily until 3:00 AM while the 10-m wind velocity does not show a net increase. In fact the sound level at location A at 3:00 AM implies a rotational speed of 21 rpm, which is just below maximum (22 rpm), even though the wind velocity at 10 m height is only 4.5 m/s and at 2 m height is less than 1 m/s. Only occasionally there are other sounds until the dawn chorus of birds at 4:00 AM and after that the near-ground wind picks up.

In figure IV.9 the 5-minute equivalent sound levels at P/Q and U relative to the sound level at A is plotted. The level differences are 3 and 6 dB, respectively, with a variation of ± 1 dB. The variations must be due to differences in sound propagation mostly, because other disturbances (such as one at 11:55 PM at P) are rare.

Comparable simultaneous measurements have been made in the night of June 2 - 3 and of June 17 – 18, 2002. In Appendix C the registrations are given, as well as the level differences between the

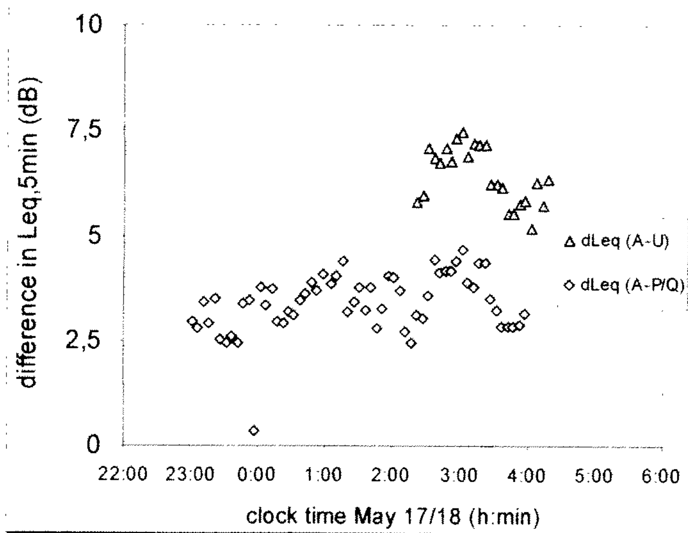


Figure IV.9: difference between simultaneously measured broad band A-weighted immission levels at location A and locations U and P/Q

distant locations P through T, V and X and the reference location A. The measured and calculated decrease in sound level with distance, relative to location A, as well as the discrepancy between both, are given in table IV.5 and figure IV.10. In all cases the wind was easterly (60° – 100°), that is: from the wind farm to the measurement location. Also there was little near-ground wind and low background sound levels from other sources.
The measured differences in table IV.5 are the difference in the equivalent sound level at a location minus the same at location A over the given measurement time T; only very few of the $L_{eq,5min}$ values were omitted from this Leq,T because they were apparently disturbed by another sound. To minimize influence of possible disturbing sounds the median of all $L_{eq,5min}$ values can be used as this value gives the prevailing difference and is thus less sensitive to the influence of disturbances; this, however, yields the same results within 0.5 dB.

Table IV.5: measured and calculated differences in sound level $L_{eq,T}$ at different locations and sound level at location A, when wind blows from the wind farm

location	R	P/Q	U	V	S	X	T
distance to western row wind farm (m)	600	750	1000	1100	1250	1900	2250
date of measurement (in 2002)	June 2/3	May 17/18, June 2/3, June 18	May 17/18	June 18	June 2/3	June 18	June 2/3
measurement time T (minutes)	200	295+200+115	120	140	190	85	195
measured difference	-3.5	-3.8 *	-6.4	-9.1	-8.5	-12.1	-1.3
calculated difference	-4.5	-4.1	-6.6	-10.6	-8.3	-13.1	-14.2
discrepancy calculation - measurement	-1.0	-0.3	-0.2	-1.5	0.2	-1.0	-12.9

*: measurement time weighted logarithmic average of resp. 3.5, 3.6 and 4.6 dB

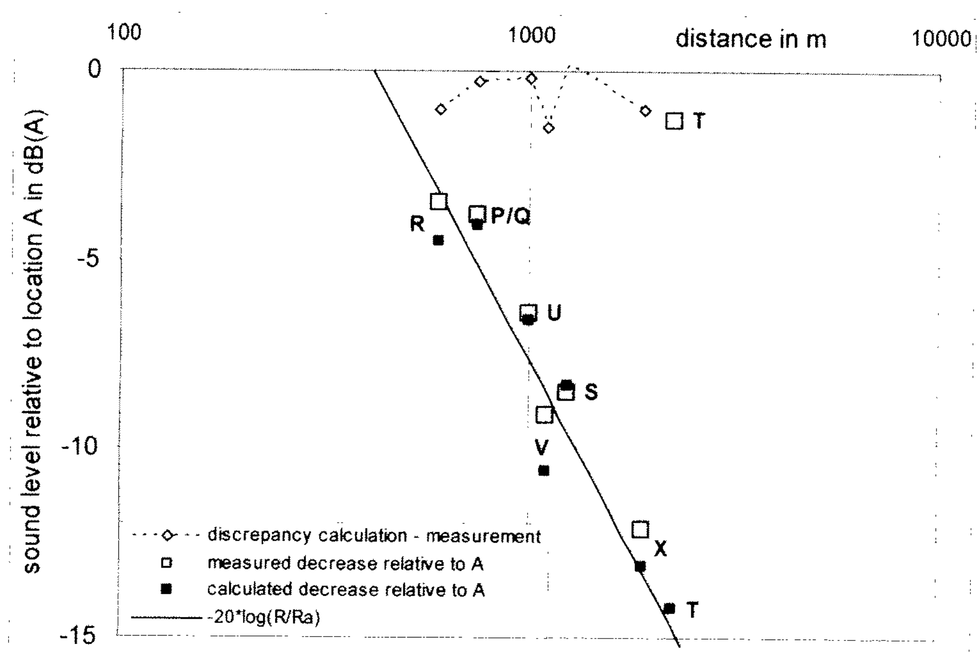


Figure IV.10: measured and calculated decrease in immission level at location P through X relative to location A, and discrepancy between both; the straight line corresponds to -20log(R/Ra)

In figure IV.10 a line is plotted corresponding to $-20\cdot\log(R/R_A)$, where R_A is the distance from A to the western turbine row. This decrease corresponds to spherical divergence only, with no attenuation due to absorption. It is clear that, with the exception of locations T (see next section), the measured decrease is close to this spherical divergence: the measured values at the locations P/Q, U, S and X are 1.4 to 1.7 dB above the plotted line, at the more northern locations R and V they are 0 to 0.3 dB below the line. Approximately the same is true for the calculated levels: the calculated values at the locations P/Q, U, S and X are 0.4 to 1.6 dB above the plotted line, at the more northern locations R and V they are 1.0 to 1.8 dB below the line.
There are two counteracting causes explaining this apparently 'almost spherical' attenuation. The first is that the wind farm cannot be considered a point source. Due to its large dimension (3 km from south to north, see figure IV.1) normal to the shortest distance from location A and locations further west, the geometrical divergence should be between cylindrical and geometrical divergence, that is: proportional to $-X\cdot\log(R/R_A)$, with $10 < X < 20$. Secondly one expects a decrease due to absorption ('excess attenuation') above the decrease due to geometrical divergence: for the Rhede turbines this excess attenuation is 1.7 dB per km.

The discrepancies between measured and calculated levels are small, especially considering the large distances involved: -0.2 to 1.5 dB. One may conclude that the calculation model is quite satisfactory in this relatively simple situation (a high sound source above a flat plane).

IV.10.2 Immission level increase due to high inversion layer?

In the night of June 2 to 3, 2002, high sound levels were measured at the most distant measurement location T, 2250 m from the wind farm. The immission sound level varied between approximately 40 and 45 dB(A) and was more variable than at the other locations (see Appendix C). The resident close to this measurement location could hear the wind farm well, at 22:30 hours describing it as: "The sound changes from 'an endless train' to a more pulsating sound; the sound grows louder en sharper. At the background is a kind of humming, comparable to the sound of a welding transformer". The sound was audible indoors.

In our research we have not met this phenomenon again. However, mr. Flight living near another wind farm south of the Rhede wind farm observed the same phenomenon: on a location appr. 750 from the closest turbine, where at night he usually measured an immission level of 42 to 44 dB(A), he measured a level of 50 to 52 dB(A) in the night of September 24, 2002. It was clear that the sound came from the nearest wind farm, but also from a second, more distant wind farm that usually was not audible here. Again, the atmosphere was stable and there was a weak near-ground easterly wind, blowing from the wind farm to the observer.

This may be a result of strong refraction of sound below an inversion layer. This inversion layer must be just above the rotor to have the highest effect, so at or just above 130 m. Suppose the turbines in the Rhede wind farm each have a sound power level L_W at a certain wind velocity. If we substitute the entire farm by one single turbine at the site of the turbine closest to location T (nr. 12), it can be calculated that the sound level of that single turbine must be $L_W + 9.4$ to produce the same immission level at T as the entire wind farm. Considering only spherical spreading, this immission level is $L_{imm} = L_W + 9.4 - 10\cdot\log(4\pi\cdot2250^2) = L_W - 68.6$. Now we replace the substitute single turbine, which can be modelled as a point source at hub height, by a vertical, 130 m heigh line source where 130 m is the inversion layer height. If the sound power levels of both point and line source are equal, the line source must have a sound power level of $L_W' = L_W + 9.4 - 10\cdot\log(130) = L_W - 11.7$

dB/m. If again the sound level decreases by geometrical (now: cylindrical) spreading only, the sound immisson level at 2250 m from this line source is $L_{imm}' = L_W - 11.7 - 10 \cdot \log(2\pi \cdot 2250) = L_W - 54.6$ dB. Comparison of the immission level due to a point source ($L_W - 68.6$) and a line source ($L_W - 54.6$) shows that the line source causes a 14 dB higher immission level. This simple calculation shows that the rise in level caused by a simplified high inversion layer is close to the observed increase (13 dB). However, more observations and data are needed to verify this hypothesis.

IV.11 Conclusion

Sound immission measurements have been made at 400 m (location A) and 1500 m (location B) from the wind park Rhede with 17 tall (98 m hub height), variable speed wind turbines. It is customary in wind turbine noise assessment to calculate immission sound levels assuming wind velocities based on wind velocities v10 at reference height (10 m) and a logarithmic wind profile. Our study shows that the immission sound level may, at the same wind velocity v10 at 10 m height, be significantly higher (up to 18 dB) in night-time than in daytime. Another, 'stable' wind profile predicts a wind velocity vh at hub height 1.8 times higher than expected and agrees excellently with the average measured night-time sound immission levels. Wind velocity at hub height may still be higher: at low wind velocities v10 up to 4 m/s, the wind velocity vh is at night up to 2.6 times higher than expected.

Thus, the logarithmic wind profile, depending only on surface roughness and not on atmospheric stability, is not a good predictor for wind profiles at night. Especially for tall wind turbines, estimates of the wind regime at hub height based on the wind velocity distribution at 10 m, will lead to an underestimate of the immission sound level at night: at low wind velocities (v10 < 4 m/s) the actual sound level will be higher than expected for a significant proportion of time. This is not only the case for a stable atmosphere, but also -to a lesser degree- for a neutral atmosphere.

The change in wind profile at night also results in lower ambient background levels then expected: at night the wind velocity near the ground may be lower than expected from the velocity at 10 m and a logarithmic wind profile, resulting in low levels of wind induced sound from vegetation. The contrast between wind turbine and ambient sound levels is therefore at night more pronounced.

Measured immission sound levels at 400 m from the nearest wind turbine almost perfectly match (average difference: 0,1 dB) sound levels calculated from measured emission levels near the turbines. From this it may be concluded that both the emission and immission sound levels could be determined accurately, even though the emission measurements were not quite in agreement with the recommended method. As both levels can be related through a propagation model, it may not be necessary to measure both: the immission measurements can be used to assess immission as well as emission sound levels.
At greater distances the calculated level may underestimate the measured level, but considering the distances involved (up to 2 km) the discrepancy is small: 1.5 dB or less.

In one night however the sound level at a distant location (over 2 km from the wind farm) was much higher than expected, probably because of an inversion layer adding more downward refracted sound. It apparently is a rare occurrence at the Rhede wind farm, and could be more significant where high inversion layers occur more often.

V THE BEAT IS GETTING STRONGER: low frequency modulated wind turbine sound

V.1 *Effect of atmospheric stability on wind turbine sound*

Atmospheric stability is not only relevant for wind turbine sound *levels*, as we saw in the preceding chapter, but also for the *character* of the sound. In conditions where a stable atmosphere is probable, distant wind turbines can produce a beating or thumping sound that is not apparent in daytime.

The magnitude of the effects of increasing stability depends on wind turbine properties such as speed, diameter and height. We will use the dimensions of the wind turbines in the Rhede wind farm, that are typical for a modern 1.5-2 MW wind turbine: hub height 100 m, blade length 35 m and rotational speed increasing with wind velocity up to a maximum value of $\Omega \cdot R$ = 73 m/s (at 20 rpm).

To calculate vertical wind velocity gradients the simple engineering formula (IV.4) will be used: $v_h = v_{ref} \cdot (h/h_{ref})^m$ (see section IV.4). In the text below we will use a value m = 0.15 for a daytime atmosphere (unstable – neutral), m = 0.4 for a stable, and m = 0.65 for a very stable atmosphere (see table VI.1). These values will be used for altitudes between 10 and 120 m.

There are now three factors influencing blade swish level when the atmosphere becomes more stable: a) the higher wind velocity gradient, b) the higher wind direction gradient, and c) the relative absence of large scale turbulence.

a. Wind velocity gradient. Rotational speed is determined by a rotor averaged wind velocity. With increasing atmospheric stability the difference in wind velocity between the upper and lower part of the rotor increases. Suppose that the wind velocity at hub height is v_{100} = 14 m/s, corresponding to v_{10} = 9.8 m/s in a neutral atmosphere in flat open grass land (roughness length 4 cm). Then in daytime (m = 0.15) the wind velocity at the lowest point of the rotor would be v_{65} = 13.1 m/s, at the highest point v_{135} = 14.6 m/s. As the blade angle does not change with rotation angle, the difference between the low tip and hub height wind velocities causes a change in angle of attack on the blade of $\Delta\alpha$ = 0.8° at 20 rpm (see appendix B, equation B.7). Between the high tip and hub height the change is smaller: 0.5°. In night-time (m = 0.4), at the same wind velocity at hub height, v_{65} is 11.8 m/s causing a change in angle of attack at the lower tip relative to hub height of 1.8° (at the high tip: v_{135} = 15.8 m/s, $\Delta\alpha$ = 1.5°). When the atmosphere is very stable (m = 0.65), wind velocity v_{65} = 10.5 m/s and the angle of attack on the low altitude tip deviates 2.9° from the angle at hub height (at the high tip: v_{135} = 17.0 m/s, $\Delta\alpha$ = 2.5°).

In fact when the lower tip passes the tower there is a greater mismatch between optimum and actual angle of attack α because there was already a change in angle of attack related to the wind velocity deficit in front of the tower. For a daytime atmosphere and with respect to the situation at hub height, the change in α associated to a blade swish level of 1 ± 0.5 dB is estimated as 2.1 ± 0.4° (see appendix, B section *C*), part of which (0.8°) is due to the wind profile and the rest to the tower. The increase in α due to the stability related wind profile change must be added to this daytime change in α. Thus, relative to the daytime (unstable to neutral) atmosphere, the change in angle of attack when the lower tip passes the mast increases with 1.0° in a stable atmosphere, and with 2.1° in a very stable atmosphere. The associated change in trailing edge (TE) sound level, as calculated from equation B.6 in

appendix B, is 3.1 ± 0.7 dB for a stable and 5.0 ± 0.8 dB for a very stable atmosphere (compared to 1 ± 0.5 dB in daytime). The corresponding total A-weighted sound level will be somewhat less as trailing edge sound is not the only sound source (but it is the dominant source; see section 4C).
At the high tip the change in angle of attack is smaller than for the low tip as there is no (sudden) tower induced change to add to the wind gradient dependent change. The change in angle of attack at the high tip in a very stable atmosphere (2.5°) is comparable to the change at the low tip in daytime, and this change is more gradual than for the low tip.

Thus we find that, for v_{100} = 14 m/s, the 1-2 dB daytime blade swish level increases to approx. 5 dB in a very stable atmosphere. The effect is stronger when wind velocity increases up to the point where friction turbulence overrides stability and the atmosphere becomes neutral. The increase in trailing edge sound level will be accompanied by a lower peak frequency (see appendix B, equation B.2). For α = 5° the shift is one octave.

b. Wind direction gradient. In a stable atmosphere air masses at different altitudes are only coupled by small scale turbulence and are therefore relatively independent. Apart from a higher velocity gradient a higher wind direction gradient is also possible, and with increasing height the wind direction may change significantly. This wind direction shear will change the angle of attack with height. Assuming the wind at hub height to be normal to the rotor, the angle of attack will decrease below and increase above hub height (or vice versa). This effect, however, is small: if we suppose a change in wind direction of 20° over the rotor height at a wind velocity of 10 m/s, the change in angle of attack between extreme tip positions at 20 rpm is only 0.25°, which is negligible relative to the wind velocity shear.

c. Less turbulence. As was shown earlier, in areas near a wind farm an increase in blade swish pulse[1] height can be explained by the synchronization of two or three pulse trains coming from the two or three closest turbines. In a stable atmosphere wind turbines can run almost synchronously because the absence of large scale turbulence leads to less variation superimposed on the constant (average) wind velocity at each turbine. In unstable conditions the average wind velocity at both turbines will be equal, but instantaneous local wind velocities will differ because of the presence of large, turbulent eddies at the scale of the inter-turbine distance. In a stable atmosphere the turbulence scale decreases with a factor up to 10, relative to the neutral atmosphere and even more relative to an unstable atmosphere [17]. In stable conditions turbines in a wind farm therefore experience a more similar wind and as a consequence their instantaneous turbine speeds are more nearly equal. This is confirmed by long term measurements by Nanahara *et al.* [2004] who analysed coherence of wind velocities between different locations in two coastal areas. At night wind velocities at different locations were found to change more coherently than they did at daytime [Nanahara 2004]. The difference between night and day was not very strong, probably because time of day on its own is not a sufficient indicator for stability.[2] The decay of coherence was however strongly correlated with turbulence intensity, which in turn is closely correlated to stability.
Near the Rhede wind farm we found that, because of the *near*-synchronicity of several turbines, sometimes two or three were in phase and the blade passing pulses coincided, and then went out of phase again [2]. This would lead to a doubling (+3 dB) or tripling (+5 dB) of

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[1] The term 'pulse' is used to indicate the upward variation in sound level

[2] In a coastal location atmospheric stability also depends on wind direction as landwards stability is a diurnal, but seawards a seasonal phenomenon. Also, a fixed duration for all nights in a year does not coincide with the time that the surface cools (between sundown and sunrise), which is a prerequisite for stability.

pulse height. If in a (very) stable atmosphere individual swish pulse heights are 3–5 dB (see section 3*a* above), synchronicity at the Rhede wind farm or similar configurations would thus lead to pulse heights of 6 – 10 dB.
Synchronicity here refers to the sound pulses from the different turbines as observed at the location of the observer. So, pulses synchronise when they arrive simultaneously. This is determined by differences in phase (rotor position) between turbines and in propagation distances of the sound from the turbines. Phase differences between turbine rotors occur because turbines are not connected and because of differences in actual performance. The place where synchronicity is observed will change when the phase difference between turbines changes. With exact synchronicity there would be a fixed interference pattern, with synchronicity at fixed spots. Because of near-synchronicity however, synchronicity will change over time and place and an observer will hear coinciding pulses for part of the time only.

A second effect of the decrease in turbulence strength is that in-flow turbulent sound level also decreases. The resulting decrease in broad band sound level lowers the minimum in the temporal variations, thereby increasing modulation depth.

We conclude that the higher wind velocity gradient and (near-) synchronicity increase blade swish levels at some distance from a wind farm. The higher infrasound level due to extra blade loading is not perceptible because of the high hearing threshold at the very low blade passing frequency. However, the effect of added boundary layer turbulence on the blade increases the levels at the higher frequencies that already were dominating the best audible part of the sound. Near a wind farm the variation in sound level will depend on the distances of the wind turbines relative to the observer: the level increase due to several turbines will reach higher levels when more turbines are at approximately equal distances and thus contribute equal immission levels. The increase in level variation, or beating, is thus at well-audible frequencies and has a repetition rate equal to the blade passing frequency.
Thus, theoretically it can be concluded that in stable conditions (low ambient sound level, high turbine sound power and higher modulation or swish level) wind turbine sound can be heard at greater distances and is of lower frequency due to absorption and the frequency shift of swish sound. It is thus a louder and more low-frequency 'thumping' sound and less the swishing sound than observed close to a daytime wind turbine.

V.2 Measurement results

V.2.1 Locations

In the summer of 2002 and 2004 wind turbine sound has been recorded in and near the Rhede wind farm on the German-Dutch border. The farm (see figure IV.1) has a straight south to north row of ten turbines at approximately 300 m intervals, running parallel to the border, and seven less regularly spaced turbines east of the straight row. Each turbine is 98 m to the hub height, and has a blade length of 35 m, and produces nominally 1.8 MW electric power.
The measurement location at dwelling R is west of the turbines, 625 m from the nearest turbine. The microphone position was at 4 m height and close to the house, but with no reflections except from the ground. The measurement location at dwelling P, 870 m south of R, was 1.5 m above a paved terrace in front of the façade of the dwelling at 750 m distance from the nearest turbine. The entire area is quiet, flat, agricultural land with some trees close to the dwellings. There is little traffic and there are no significant permanent human sound sources.

A third dwelling Z is in Boazum in the northern part of the Netherlands, 280 m west of a single, two-speed turbine (45 m hub height, 23 m blade length, 20/26 rpm). The area is again quiet, flat and agricultural. The immission measurement point is at 1.5 m height above gravel near the dwelling. This measurement site is included here to show that the influence of stability on blade swish levels occurs also with smaller, single turbines. At all locations near dwellings the microphone was fitted in a 9 cm diameter foam wind screen.
Table 1 gives an overview of measurement (start) time and date, of observed turbine speed and of wind velocity and direction, for situations from which results will be given below. The wind velocity at hub height v_{hub} has been determined from turbine rotation speed N or sound power level L_W ([2], the relation v_{hub} – N follows from ref. 3 and 11 in [1]). The wind velocity v_{10} at 10 m height was continuously measured at or near location A, except for location Z, where data from several meteorological stations were used showing that the wind was similar and nearly constant in the entire nothern part of the Netherlands. In all cases there were no significant variations in wind velocity at the time of measurement. Wind velocity at the microphone was lower than v_{10} because of the low microphone height and shelter provided by trees nearby. Wind direction is given in degrees relative to north and clockwise (90° is east).
The spectra near a turbine were measured with the microphone just above a hard surface at ground level 100 m downwind of a turbine in compliance with IEC 61400 [14] as much as possible (non-compliance did not lead to differences in result [2]; for reasons of non-compliance, see [34]). The levels plotted are immission levels: measured Leq minus 6 dB correction for coherent reflection against the hard surface [16]. The plotted levels near the dwellings are also immission levels: measured Leq minus 3 dB correction for incoherent reflection at the façade for dwelling P, or measured Leq without any correction for dwellings R and Z.

Table V.1: overview of measurement locations and times and of turbine speed and wind

Location	measurement date	time	turbine speed (rpm)	wind velocity (m/s) v_{10}	v_{hub}	wind direction (° north)
Dwelling P	June 3, 2002	00:45	20	5	14	100
Turbine 7	June 3, 2002	06:30	19	5	15	100
Turbine 1	June 3, 2002	06:45	19	5	15	100
Dwelling R Turbine 16	Sep. 9, 2004	23:07	18	4	14	80
Dwelling Z	Oct. 18, 2003	01:43	26	3	6	60

At dwelling P at the time of measurement the beat in the turbine sound was very pronounced. In the other measurements (dwellings R and Z) the beating was not as loud. The measurements near turbine 16 and dwelling R at 23:07 on September 9 were performed simultaneously.

V.2.2 Frequency response of instruments

For the Rhede measurements sound was recorded on a TASCAM DA-1 DAT-recorder with a precision 1" Sennheiser MKH 20 P48 microphone. The sound was then sampled in 1-second intervals on a Larson Davis 2800 frequency analyser. From 1 to 10 000 Hz the frequency response of the DAT-recorder and LD2800 analyser have been determined with a pure tone electrical signal as input. The LD2800 response is flat (±1 dB) for all frequencies. The DAT-recorder is a first order high pass filter with a corner frequency of 2 Hz. The frequency response of the microphone was of most influence and has been determined relative to a B&K ½" microphone type 4189 with a known frequency response [20]. Equivalent spectral sound levels with both microphones in the same sound field (approx. 10 cm mutual distance) were compared. For frequencies of 2 Hz and above the entire measurement chain is within 3 dB equivalent to a series of two high pass filters with corner frequencies of $f_1 = 4$ Hz and $f_2 = 9$ Hz, or a transfer function equal to $-20 \cdot \log[1+(f_1/f)^2]$ $-20 \cdot \log[1+(f_2/f)^2]$. For frequencies below 2 Hz this leads to high signal reductions (< -40 dB) and consequentially low signal to (system) noise ratios. Therefore values at frequencies < 2 Hz are not presented.

For the Boazum measurements sound was recorded on a Sharp MD-MT99 minidisc recorder with a 1" Sennheiser ME62 microphone. The frequency response of this measurement chain is not known, but is assumed to be flat in the usual audio frequency range. Simultaneous measurement of the broad band A-weighted sound level were done with a precision (type 1) 01dB sound level meter. Absolute precision is not required here as the minidisc recorded spectra are only used to demonstrate relative spectral levels. Because of the ATRAC time coding of a signal, a minidisc recording does not accurately follow a level change in a time interval < 11.6 ms. This is insignificant in the present case as the 'fast' response time of a sound level meter is much slower (125 ms).

V.2.3 Measured emission and immission spectra

Recordings were made at evening, night or early morning. On June 3, 2002, sound was recorded at dwelling P at around midnight and early in the morning near two turbines (numbers 1 and 7). At P at these times a distinct beat was audible in the wind turbine sound. In figure V.3, 1/3 octave band spectra of the recorded sound at P and at both turbines have been plotted. In each figure A, B and C, 200 sound pressure spectra sampled in one-second intervals, as well as the energy averaged spectrum of the 200 samples have been plotted. The standard deviation of 1/3 octave band levels is typically 7 dB at very low frequencies, decreasing to approx. 1 dB at 1 kHz. The correlation coefficient ρ between all unweighted 1/3 octave band levels and the overall A-weighted sound level has also been plotted for each 1/3 octave band frequency.

For frequencies below approximately 10 Hz the sound is dominated by the thickness sound associated with the blade passing frequency and harmonics. In the rest of the infrasound region and upwards, in-flow turbulence is the dominant sound producing mechanism. Gradually, at frequencies above 100 Hz, trailing edge sound becomes the most dominant source, declining at high frequencies of one to several kHz. Trailing edge sound is more pronounced at turbine 1 (T1) compared to turbine 7 (T7), causing a hump near 1000 Hz in the T1 spectra. At very high frequencies (> 2 kHz) sometimes higher spectral levels occur due to birds.

It is clear from the spectra that most energy is found at lower frequencies. However, most of this sound is not perceptible. To assess the infrasound level relevant to human perception it can be expressed as a G-weighted level [ISO 1995], With G-weighting sound above the infrasound range is suppressed. The average infrasound perception threshold is 95 dB(G) [Jakobsen 2004]. The measured G-weighted levels are 15-20 dB below this threshold: 80.5 and 81.1 dB(G) near turbines 1 and 7 respectively, and 76.4 dB(G) at the façade.

The correlations show that variations in total A-weighted level near the turbines are correlated with the 1/3 octave band levels with frequencies from 400 through 3150 Hz (where $\rho > 0.4$), which is trailing edge sound. This is one octave lower (200 - 1600 Hz) for the sound at the façade: the higher frequencies were better absorbed during propagation through the atmosphere.

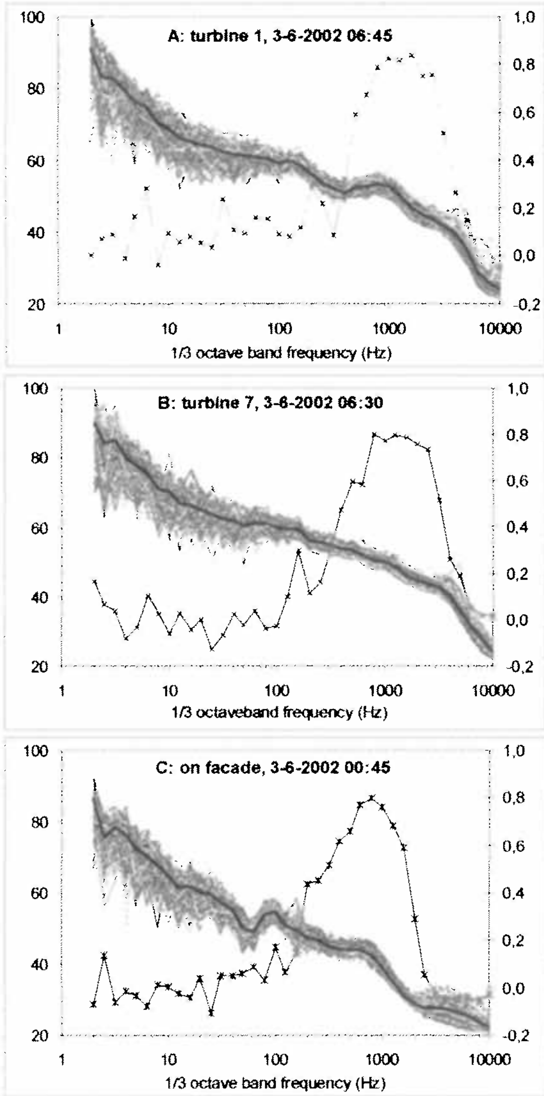

Figure 3: left axis (in dB): 200 consecutive, unweighted and 1 second spaced 1/3 octave band levels (thin lines), and average spectral level (thick line) near turbines 1 and 7, and near dwelling P;
right axis: coefficient of correlation (line with markers) at each 1/3 octave band frequency between all 200 1/3 octave band levels and overall A-weighted levels

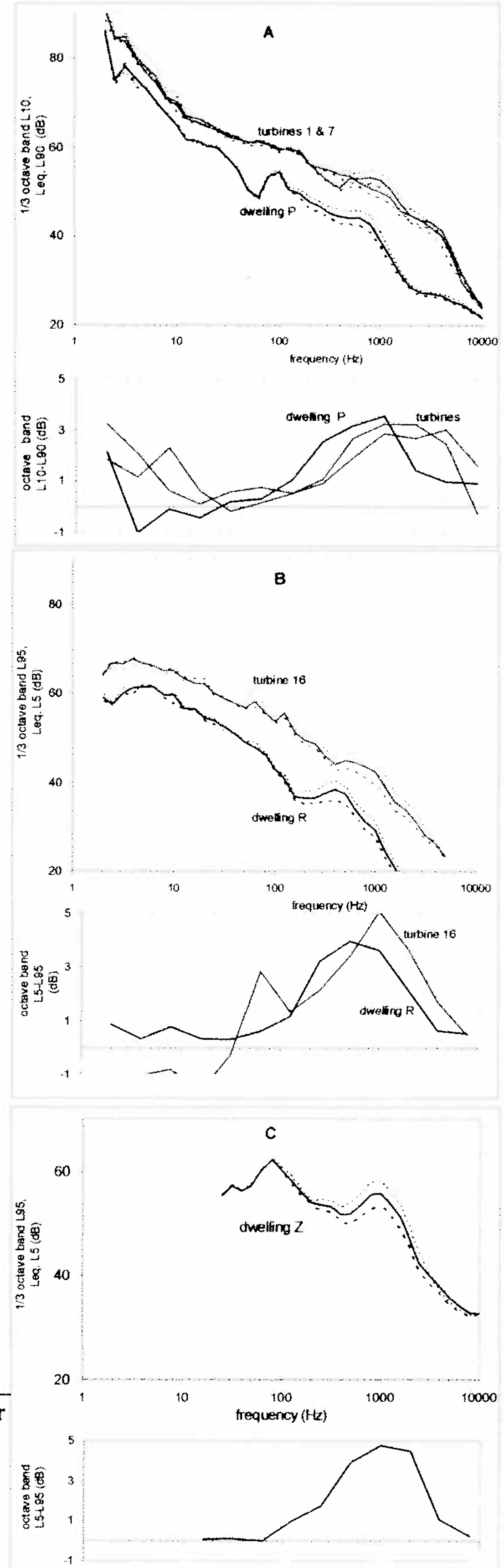

Figure V.4: upper panels A,B,C: 1/3 octave band Leq near windturbines and dwellings (thick lines) and Leq of all samples with resp. 5% highest (thin dotted lines) and 5% lowest values of broad band L_A (thick dotted lines). lower panels: difference between Leq of 5- and 95-percentile octave band levels

The façade spectra in figure V.3C show a local minimum at 50-63 Hz, followed by a local maximum at 80-100 Hz.[1] This is caused by interference between the direct sound wave and the wave reflected by the façade at 1.5 m from the microphone: for wave lengths of approx. 6 m (55 Hz) this leads to destructive interference, for wave lengths of 3 m (110 Hz) to constructive interference.

In figure V.4A the three average spectra at the same locations as in figure V.3A-C have been plotted, but now for a total measurement time of approx. 9.5 (façade), 5 (T7) and 6 (T1) minutes. For each of these measurement periods the average of the 5% of samples with the highest broad band A-weighted sound level (*i.e.* the equivalent spectral level of the L_{A5} percentile) has also been plotted, as well as the 5% of samples with the lowest broad band level (L_{A95}). The range in A-weighted broad band level can be defined as the difference between the highest and lowest value: $R_{bb} = L_{Amax} - L_{Amin}$. Similarly the range per 1/3 octave or octave band R_f can be defined by the difference in spectral levels corresponding to L_{Amax} and L_{Amin}. The difference between L_{A5} and L_{A95} is a more stable value, avoiding possibly incidental extreme values, especially when spectral data are used. $R_{bb,90}$ is defined as the difference in level between the 5% highest and the 5% lowest broad band sound levels: $R_{bb,90} = L_{A5} - L_{A95}$. For spectral data, $R_{f,90}$ is the difference between spectral levels associated with L_{A5} and L_{A95}. Values of $R_{f,90}$ are plotted in the lower part of figure V.4A (here octave bandlevels have been used to avoid the somewhat 'jumpy' behaviour of the 1/3 octave band levels). Close to turbines 1 and 7 R_{bb} is 4.8 and 4.1 dB, respectively. $R_{bb,90}$ is 3.2 and 2.6 dB, which is almost the same as $R_{f,90}$ (3.2 and 3.0 dB) at 1000–4000 Hz. Further away, at the façade, R_{bb} is comparable to the near turbine values: 4.9 dB. $R_{bb,90}$ at the façade is 3.3 dB and again almost the same as maximum $R_{f,90}$ (3.5 dB) at 1000 Hz.

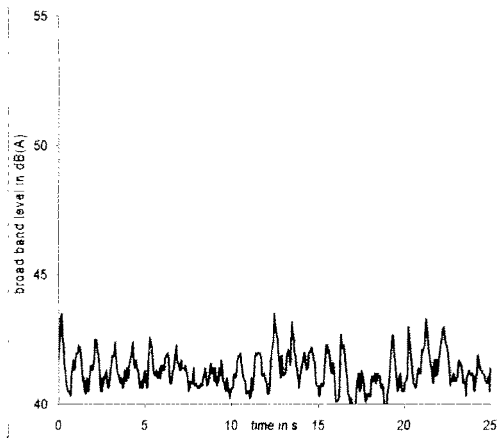

Figure V.5: broad band A-weighted immission sound level near turbine 17 (upper plot) and close to dwelling R (lower plot)

Also, close to the turbine there is a low frequency maximum in $R_{f,90}$ at 2 (or 8) Hz that is also present at the façade, indicating that the modulation of trailing edge sound is correlated in time with the infrasound caused by the blade movement.

Figure V.4B presents similar plots for the average spectra and the L_{A5} and L_{A95} spectra at dwelling R and near turbine T16 over a period of 16 minutes. Close to the turbine the broadband $R_{bb,90}$ is 3.7 dB; octave band $R_{f,90}$ is highest (5.1 dB) at 1000 Hz. Near R broad band $R_{bb,90}$ is also 3.7 dB, and octave band $R_{f,90}$ is highest (4.0 dB) at 500 Hz. The R_{bb} ranges are 2.3–2.5 dB higher than the 90% ranges $R_{bb,90}$.

A 25 second part of this 16 min period is shown in figure V.5. The broad band level L_A changes with time at T16 and R, showing a more or less regular variation with a period of approximately 1 s (= $1/f_B$). In these measurements the infrasound level was lower than in the previous measurements at dwelling P where beating was more pronounced. G-weighted sound level during the 16 minutes at R was 70.4 dB(G), and at T16 77.1 dB(G).

Finally figure V.3C gives average spectra over a period of 16 minutes at dwelling Z. $R_{f,90}$ is now highest (4.8 dB) at 1 kHz, and broadband $R_{bb,90}$ is 4.3 dB (R_{bb} = 5.9 dB). The turbine near

[1] In an FFT spectrum minima are at 57 and 170 Hz, maxima at 110 and 220 Hz

Z is smaller and lower, but rotates faster than the Rhede turbines; for a hub height wind velocity of 6 m/s the expected calculated increase in trailing edge sound for the lower tip relative to the day time situation is 2.0 ± 0.8 dB for a stable, and 2.9 ± 0.8 dB for a very stable atmosphere. For this turbine a peak trailing edge sound level is expected (according to equation B.2 in appendix B) at a frequency of 1550/a Hz ≈ 400 – 800 Hz.

In all cases above the measured sound includes ambient background sound. Ambient background sound level could not be determined separately at the same locations because the wind turbine(s) could not be stopped (it has been shown elsewhere that it is a flaw in noise regulation to make independent noise assessment procedurally impossible because of its dependency on wind turbine owner's consent [34]). However, at audible frequencies it could be ascertained by ear that wind turbine sound was dominant. At infrasound frequencies this could not be ascertained. But if significant ambient sound were present, subtracting it from the measured levels would lead to lower (infrasound) sound levels, which would not change the conclusion, based on the G-weighted level, that measured infrasound must be considered inaudible.

V.2.4 Beats caused by interaction of several wind turbines

In the previous section we saw that measured variations in broad band sound level (R_{bb}) were 4 to 6 dB. In figure V.6 a registration is given of the sound pressure level every 50 msec over a 180 seconds period, taken from a DAT-recording on a summer night (June 3rd, 0:40 h) on a terrace of a dwelling at 750 m west of the westernmost row of wind turbines (this sound includes the reflection on the façade at 2 m). In this night stable conditions prevailed (m = 0.45 from the wind velocities in table 1). Turbines 12 and 11 are closest at 710 and 750 m, followed by turbines 9 and 14 at 880 and 910 m. Other turbines are more than 1 km distant and have an at least 4 dB lower immission level than the closest turbine has.

In figure V.6 there is a slow variation of the 'base line' (minimum levels) probably caused by variations in wind velocity and atmospheric sound transmission. There is furthermore a

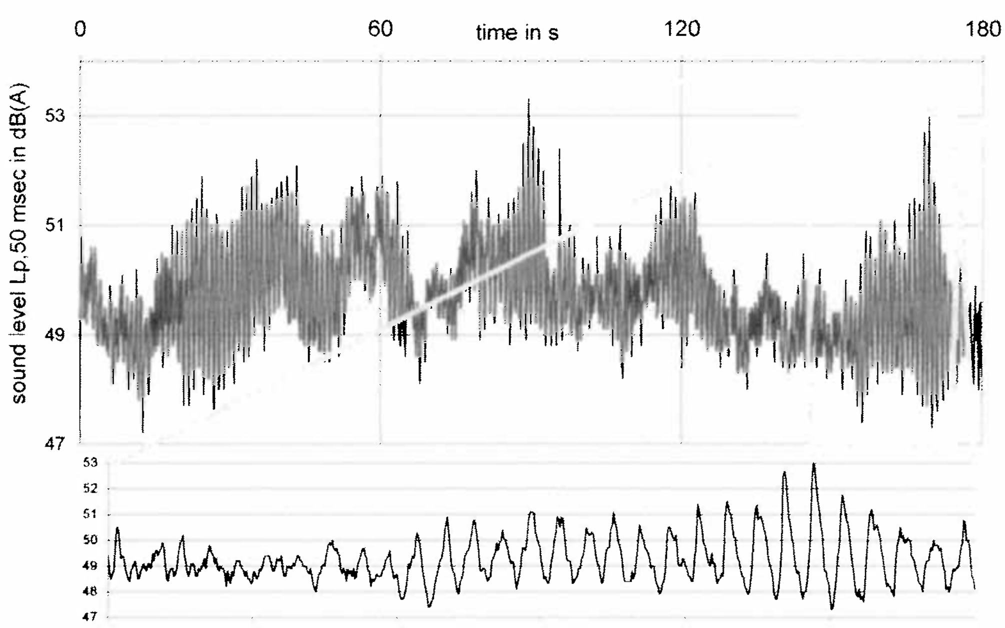

Figure V.6: broad band A-weighted immission at façade of dwelling P

variation in dynamic range: a small difference between subsequent maximum and minimum levels of less than 2 dB is alternated by larger differences.
The sequence in figure V.6 begins when the turbine sound is noisy and constant within 2 dB. After some time (at t = 155 s) regular pulses appear with a maximum height of 3 dB, followed by a short period with louder (5 dB) and steeper (rise time up to 23 dB/s) pulses. The pulse frequency is equal to the blade passing frequency. Then (t > 180 s) the pulses become weaker and there is a light increase in wind velocity.
This was one of the nights where a distinct beat was audible: a period with a distinct beat alternating with a period with a weaker or no beat, repeated more or less during the entire night. This pattern is compatible with a complex of three pulse trains with slightly different repetition frequencies of ca. 1 Hz. When the pulses are out of phase (around 150 s in figure V.6), there are only 1 dB variations. When 2 of them are in phase (around 160 s) pulse height is doubled (+3 dB), and tripled (+5 dB, 170 s) when all three are in phase. The rotational speed of the turbines at the time was 20 rpm, so the repetition rate of wings passing a mast was 1 Hz.
The low number of pulse trains, compared to 17 turbines, is compatible with the fact that only a few turbines dominate the sound immission at this location. The calculated immission level is predominantly caused by two wind turbines (numbers 11 and 12: see figure IV.1, contributing 35% of the A-weighted sound energy), less by two others (9 and 14; 21%), so only 4 turbines contribute more than half of the sound immission energy.

In figure V.7 the equivalent 1/3 octave band spectrum at the façade of P has been plotted for the period of the beat (165 < t < 175 s in figure 6, spectra sampled at a rate of 20 s^{-1}), as well as the equivalent spectrum associated with the 5% highest (L_{A5} = 52.3 dB(A)) and the 5% lowest (L_{A95} = 47.7 dB(A)) broad band levels within this 10 s period, and the difference between both. As in the similar spectra in figure 4 we see that the beat corresponds to an increase at frequencies where trailing edge sound dominates: the sound pulses correspond to 1/3 octave band levels between 200 and 1250 Hz and are highest at 800 Hz. In figure V.7 also the equivalent 1/3 octave band levels are plotted for the period after beating where the wind was picking up slightly (t > 175 s in figure 6). Here spectral levels above 400 Hz are the same or slightly lower as on average at the time of beating, but at lower frequencies down to 80 Hz (related to in-flow turbulence) levels now are 1 to 2 dB higher. The increase in the 'more wind' spectrum at high frequencies (> 2000 Hz) is probably from rustling tree leaves.

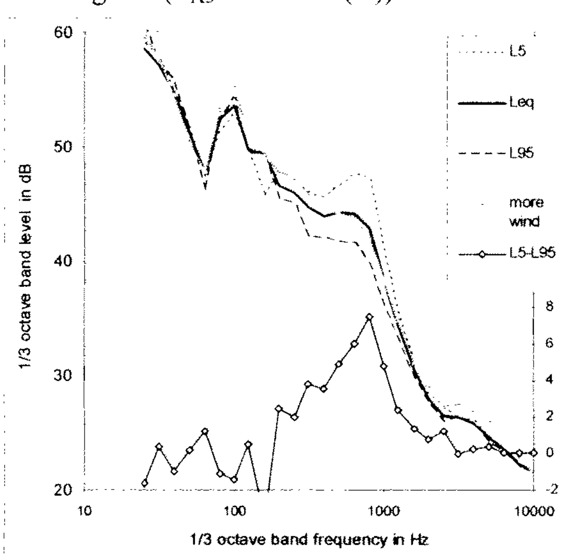

Figure 7: 1/3 octave band levels at façade of dwelling P during beating (L_{eq}, L_{10} and L_{90}) and when wind speed is picking up (L_{eq})

Figure V.8 shows sound power spectra for a period with a distinct beat (150 < t < 175 s in figure 6), and a period with a weak or no beat (130 < t < 150 s). Each spectrum is an FFT of 0.2 Hz line width from broad band A-weighted immission sound pressure level values. The frequencies are therefore *modulation*, not sound frequencies. The ordinate spans 20 dB. The spectra show that distinct beating is associated with higher total A-weighted levels at the blade passing frequency and its harmonics. As has been shown above, the higher level is related to the frequency range of trailing edge sound. Infrasound frequencies linked to thickness sound are negligible in total A-weighted sound levels. When beating is weaker but there is more wind (t > 175 s), the level of the odd harmonics (base frequency k = 1, and k = 3) is lower than during 'beat', whereas the first two even harmonics (k = 2, 4) are equally loud, indicating more distorted (less sinusoidal) and lower level pulses. It is important to realize that the periodic variation as represented in figure V.8 is the result from a wind farm, not from a single turbine.

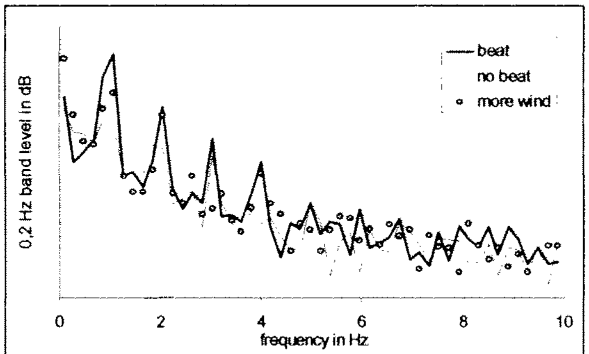

Figure 8: sound power spectrum of A-weighted broad band immission sound level at façade of dwelling P when beating is distinctly or not audible and with slightly increased wind speed

In long term measurements near the Rhede wind farm, where average and percentile sound levels were determined over 5 minute periods, periods where wind turbine sound was dominant could be selected with a criterion ($R_{bb,90} = L_{A5} - L_{A95} \leq 4$ dB) implying a fairly constant source with less than 4 dB variation for 90% of the time [2]. The statistical distribution of the criterion values has been plotted in 1 dB intervals in figure 9 for the two long term measurement locations A and B (see figure 2). Total measurement times –with levels in compliance with the criterion- were 110 and 135 hours, respectively. Relative to dwellings P and R, one location (A, 400 m from nearest turbine) is closer to the turbines, the other (B, 1500 m) is further. The figure shows that the criterion value (cut off at 4 dB) at both locations peaks at 2.5 dB. Also plotted in figure 9 is the value of $L_{Amax} - L_{Aeq}$ (while $R_{bb,90} \leq 4$ dB), peaking at 3.5 dB at both locations. Finally, the difference between maximum and minimum level within 5 minute periods, $L_{Amax} - L_{Amin} = R_{bb}$, peaks at 4.5 dB (location A) and 5.5 dB (B). Where $R_{bb} > 7$ dB, the distributions are influenced by louder (non-turbine) sounds, such as from birds. Extrapolation of the

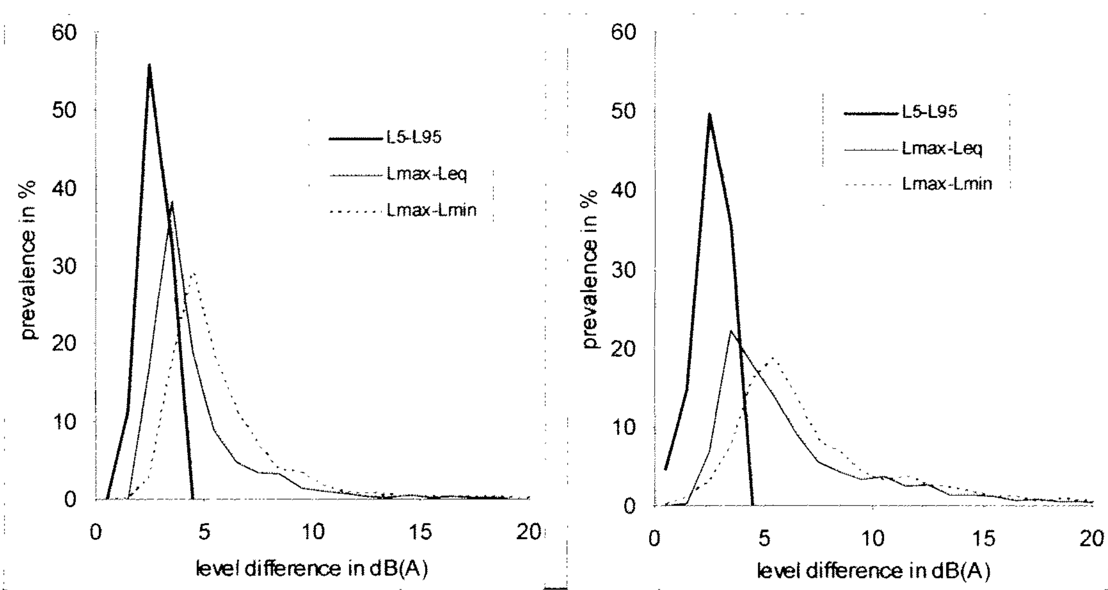

Figure 9: statistical distribution of level differences (in 1 dB-classes) between high and low sound levels within 5 minute periods at 400 m (left) and 1500 m (right) from the nearest wind turbine

distribution from lower values suggests that the maximum range R_{bb} due to the wind farm is 8.5 dB (location A) to 9.5 dB (B). This is 4 dB more than the most frequently occurring ranges at both locations.

V.2.5 Summary of results

In table 2 the level variations due to blade swish as determined in the previous sections have been summarised. Some values not presented in the text have been added. The ranges are presented as R_{bb} and $R_{bb,90}$. The latter is of course a lower value as it leaves out high and low excursions occurring less than 10% of the time. The time interval over which these level differences occur differ: from several up to 16 minutes for the short term measurements, where wind conditions can be presumed constant, up to over 100 hours at locations A and B.

Table V.2: level variation in modern wind turbine [1)] sound due to blade swish, in dB

	Location	Reference	Atmospheric condition	R_{bb} L_{Amax}-L_{Amin}	$R_{bb,90}$ L_{A5}-L_{A95}
Calculated results					
Single turbine		section 3*a*	neutral	1.5 ± 0.5	
		section 3*a*	stable	3.1 ± 0.7	
		section 3*a*	very stable	5.0 ± 0.8	
N equidistant turbines			(very) stable	single + 10·logN	
Measured results					
Single turbine		[8]	unspecified	< 3	
Single turbine	Near T1	fig. 2A		4.8	3.2
	Near T7	fig. 2A		4.1	2.6
	Near T16	fig. 2B		6.0	3.7
	dwelling Z	fig. 2C	stable	5.9 [2)]	4.3
Multiple turbines	dwelling R	fig. 2B		6.2	3.7
	façade dwelling P	fig. 2A		4.9	3.3
	façade P + beat	fig. 5		5.4	
	Location A	fig. 6A	long term, stable	4.5 (most frequent) 8.5 (maximum)	
	Location B	fig. 6B		5.5 (most frequent) 9.5 (maximum)	

notes: 1) hub height 100 m, rotor diameter 70 m, 20 rpm
2) for this turbine (hub height 45 m, diameter 46 m, 26 rpm) R_{bb} < 3.7 dB was calculated

V.3 Perception of wind turbine sound

In a review of literature on wind turbine sound Pedersen concluded that wind turbine noise was not studied in sufficient detail to be able to draw general conclusions, but that the available studies indicated that at relatively low levels wind turbine sound was more annoying than other sources of community noise such as traffic [Pedersen 2003]. In a field study by Pedersen and Persson Waye [2004] 8 of 40 respondents living in dwellings with (calculated) maximum outdoor immission levels of 37.5 - 40.0 dB(A) were very annoyed by the sound, and at levels above 40 dB(A) 9 of 25 respondents were very annoyed. The correlation between sound level (in 2.5 dB classes) and annoyance was significant ($p < 0.001$). In this field study annoyance was correlated to descriptions of the sound characteristics, most strongly to swishing with a correlation coefficient of 0.72 [Pedersen *et al* 2004]. A high degree of annoyance is not expected at levels below 40 dB(A), unless the sound has special features such as a low-frequency components or an intermittent character [WHO 2000].

Psychoacoustic characteristics of wind turbine sound have been investigated by Persson-Waye and Öhrström in a laboratory setting with naive listeners (students not used to wind turbine sound): the most annoying sound recorded from five different turbines were described as 'swishing', 'lapping' and 'whistling', the least annoying as 'grinding' and 'low frequency' [Persson Waye *et al* 2002]. People living close to wind turbines, interviewed by Pedersen *et al.*, felt irritated because of the intrusion of the wind turbines in their homes and gardens, especially the swishing sound, the blinking shadows and constant rotation [Pedersen *et al* 2004].

Our experience at distances of approx. 700 to 1500 m from the Rhede wind farm, with the turbines rotating at high speed in a clear night and pronounced beating audible, is that the sound resembles distant pile driving. When asked to describe the sound of the turbines in this wind farm, a resident compares it to the surf on a rocky coast. A resident living further away from the wind farm (1200 m) likens the sound to an 'endless train'. Another resident near a set of smaller wind turbines, describes the sound as that of a racing rowing boat (where rowers simultaneously draw, also creating a periodic swish). On the website of MAIWAG, a group of citizens from villages near four wind farms in the south of Cumbria (UK), the sound is described as 'an old boot in a tumble dryer', ans also as 'Whumph! Whumph! Whumph!'. Several residents near single wind turbines remark that the sound often changing to clapping, thumping or beating when night falls: 'like a washing machine'. It is common in all descriptions that there is noise ('like a nearby motorway', 'a B747 constantly taking of') with a periodic increase superimposed. In all cases the sound acquires this more striking character late in the afternoon or at night, especially in clear nights and downwind from a turbine.
Part of the relatively high annoyance level and the characterisation of wind turbine sound as lapping, swishing, clapping or beating may be explained by the increased fluctuation of the sound. Our results in table V.2 show that in a stable atmosphere measured fluctuation levels are 4 to 6 dB for single turbines, and in long term measurements (over many 5 minute periods) near the Rhede wind farm fluctuation levels of approx. 5 dB are common but may reach values up to 9 dB.
The level difference associated with an amplitude modulation (AM) factor mf is:

$$\Delta L = 20 \cdot \log((1+mf)/(1-mf)) \qquad \text{(V.2a)}$$

The modulation factor mf is the change in sound pressure amplitude due to modulation, relative to the average amplitude. For $\Delta L < 9$ dB a good approximation (±5%) is:

$$mf = 0.055 \cdot \Delta L \qquad \text{(V.2b)}$$

Now when ΔL rises from 3 dB. presumably a maximum value for a daytime (unstable or neutral) atmosphere, to 6 dB, mf rises from 17% to 33%. For a maximum value of $\Delta L = 9$ dB, mf is 50%.

Fluctuations are perceived as such when the modulation frequencies are less than 20 Hz. Human sensitivity for fluctuations is highest at $f_{mod} = 4$ Hz, which is the frequency typical for rhythm in music and speech [Zwicker *et al* 1999], and for frequencies of the modulated sound close to 1 kHz. For wind turbines we found that a typical modulation frequency is 1 Hz, modulating the trailing edge sound that itself is at frequencies of 500 – 1000 Hz. So human sensitivity for wind turbine sound fluctuations is relatively high.

Fluctuation strength can be expressed in a percentage relative to the highest perceptible fluctuation strength (100%) or in the unit vacil [Zwicker *et al* 1999]. The reference value for the absolute fluctuation strength is 1 vacil, equalling a 60 dB, 1 kHz tone, 100% amplitude-modulated at 4 Hz [Zwicker *et al* 1999].
For an AM pure tone as well as AM broad band noise, absolute fluctuations strength is zero until $\Delta L \approx 3$ dB, then increases approximately linearly with modulation depth for values up to 1 vacil. For a broad band noise level L_A the fluctuation strength F_{bb} can be written as [Zwicker *et al* 1999]:

$$F_{bb} = \frac{5.8\cdot(1.25mf-0.25)(0.05\cdot L_A - 1)}{(f_{mod}/5\text{ Hz})^2 + (4\text{ Hz}/f_{mod}) + 1.5} \quad \text{vacil} \qquad \text{(V.3a)}$$

With typical values for wind turbine noise of $f_{mod} = 1$ Hz and $L_A = 40$ dB(A), this can be written as $F_{bb} = 1.31\cdot(mf-0.2)$ vacil or, when $\Delta L < 9$ dB:

$$F_{bb} = 0.072\cdot(\Delta L - 3.6) \quad \text{vacil} \qquad \text{(V.3b)}$$

When ΔL increases from 3 to 6 dB, F_{bb} increases from negligible to 0.18 vacil. For the high fluctuation levels found at locations A and B (ΔL = 8 - 9 dB), F_{bb} is 0.32 to 0.39 vacil.

It can be concluded that, in a stable atmosphere, the fluctuations in modern wind turbine sound can be readily perceived. However, as yet it is not clear how this relates to possible annoyance. It can however be likened to the rhythmic beat of music: pleasant when the music is appreciated, but distinctly intrusive when the music is unwanted.

The hypothesis that these fluctuations are important, is supported by descriptions of the character of wind turbine sound as 'lapping', 'swishing', 'clapping', 'beating' or 'like the surf'. Those who visit a wind turbine in daytime will usually not hear this and probably not realise that the sound can be rather different in conditions that do not occur in daytime. This may add to the frustration of residents: "Being highly affected by the wind turbines was hard to explain to people who have not had the experiences themselves and the informants felt that they were *not being believed*" [Pedersen *et al* 2004]. Persson-Waye *et al* [2002] observed that, from five recorded different turbine sounds "the more annoying noises were also paid attention to for a longer time". This supported the hypothesis that awareness of the noise and possibly the degree of annoyance depended on the content (of intrusive character) of the sound.

Fluctuations with peak levels of 3 – 9 dB above a constant level may have effects on sleep quality. The Dutch Health Council [2004] states that "at a given L_{night} value, the most unfavourable situation in terms of a particular direct biological effect of night-time noise is not, as might be supposed, one characterised by a few loud noise events per night. Rather, the worst scenario involves a number of noise events all of which are roughly 5 dB(A) above the threshold for the effect in question." For transportation noise (road, rail, air traffic) the threshold for motility (movement), a direct biological effect having a negative impact on sleep quality, is a sound exposure level per sound event of SEL = 40 dB(A) in the bedroom [Health Council 2004]. The pulses in figure 6 have SEL-values up to 50 dB(A), but were measured on the façade. With an open window facing the wind turbines indoor SEL-values may exceed the threshold level. In other situations this of course depends on distance to and sound power of the turbines and on the attenuation between façade and bedroom. It is not clear whether the constant and relatively rapid repetition of wind turbine sound beats will have more or less effect on sleep quality, compared to vehicle or airplane passages. Pedersen and Persson Waye [2004] found that at dwellings where the (outdoor) sound level due to wind turbines exceeded 35 dB(A), 16% of 128 respondents reported sleep disturbance by this sound, of whom all but two slept with a window open in summer.

V.4 Conclusion

Atmospheric stability has a significant effect on wind turbine sound, especially for modern, tall turbines.

First, it is related to a change in wind profile causing strong, higher altitude, winds while at the same time wind close to the ground may become relatively weak. High sound immission levels may thus occur at low ambient sound levels, a fact that has not been recognised in noise assessments where a neutral or unstable atmosphere is usually implied. As a result, wind turbine sound that is masked by ambient wind-related sound in daytime, may not be masked at night time. This has been dealt with elsewhere (see chapter IV).

Secondly, the change in wind profile causes a change in angle of attack on the turbine blades. This increases the thickness (infra)sound level as well as the level of trailing edge (TE) sound, especially when a blade passes the tower. TE sound is modulated at the blade passing frequency, but it is a high frequency sound, well audible and indeed the most dominant component of wind turbine noise. The periodic increase in sound level when the blade passes the turbine tower, blade swish, is a well known phenomenon. Less well known is the fact that increasing atmospheric stability creates greater changes in the angle of attack over the rotor plane that add up with the change near the tower. This results in a thicker turbulent TE boundary layer, in turn causing a higher swish level and a shift to somewhat lower frequencies. It can be shown theoretically that for a modern, tall wind turbine in flat, open land the angle of attack at the blade tip passing the tower changes with approx. 2° in daytime, but this value increases with 2° when the atmosphere becomes very stable. The calculated rise in sound level during swish then increases from 1–2 dB to 4–6 dB. This value is confirmed by measurements at single turbines in the Rhede wind farm where maximum sound levels rise 4 to 6 dB above minimum sound levels within short periods of time.

Thirdly, atmospheric stability involves a decrease in large scale turbulence. Large fluctuations in wind velocity (at the scale of a turbine) vanish, and the coherence in wind velocity over distances as great as or larger than the size of an entire wind farm increases. As a result turbines in the farm are exposed to a more constant wind and rotate at a more similar speed with less fluctuations. Because of the near-synchronicity, blade swishes may arrive simultaneously for a period of time and increase swish level. The phase difference between turbines determines where this amplification occurs: whether the swish pulses will coincide at a location depends on this phase difference and the propagation time of the sound. In an area where two or more turbines are comparably loud the place where this amplification occurs will sweep over the area with a velocity determined by the difference in rotational frequency. The magnitude of this effect thus depends on stability, but also on the number of wind turbines and the distances to the observer. This effect is in contrast to what was expected, as it seemed reasonable to suppose that turbines would behave independently and thus the blade swish pulses from several turbines would arrive at random, resulting in an even more constant level than from one turbine. Also, *within* a wind farm the effect may not be noticed, since comparable positions in relation to two or more turbines are less easily realised at close distances.

Sound level differences L_{Amax}-L_{Amin} (corresponding to swish pulse heights) within 5 minute periods over long measurement periods near the Rhede wind farm show that level changes of approximately 5 dB occur for an appreciable amount of time and may less often be as high as 8 or 9 dB. This level difference did not decrease with distance, but even increased 1 dB when distance to the wind farm rose from 400 m to 1500 m. The added 3-5 dB, relative to a single turbine, is in agreement with simultaneously arriving pulses from two or three approximately equally loud turbines.
The increase in blade swish level creates a new percept, fluctuating sound, that is absent or weak in neutral or unstable atmospheric conditions. Blade passing frequency is now an important parameter as a modulation frequency (not as an infrasound frequency). Human perception is most sensitive to modulation frequencies close to 4 Hz of sound with a frequency of approx. 1 kHz. The hypothesis that fluctuations are important is supported by descriptions given by naïve listeners as well as residents: turbines sound like 'lapping', 'swishing', 'clapping', 'beating' or 'like the surf'. It is not clear to what degree this fluctuating character determines the relatively high annoyance caused by wind turbine sound and to a deterioration of sleep quality. Further research is necessary into the perception and annoyance of wind turbine sound, with correct assumptions on the level and character of the sound. Also the sound exposure level of fluctuations in the sound in the bedroom must be investigated to be able to assess the effects on sleep quality.

It is obvious that in wind turbine sound measurements atmospheric stability must be taken into account. When the impulsive character of the sound is assessed, this should be carried out in relation to a stable atmosphere, as that is the relevant condition for impulsiveness. Also sound immission should be assessed for stable conditions in all cases where night time is the critical noise period. Wind velocity at low heights is not a sufficient indicator for wind turbine performance. Specifically, when ambient sound level is considered as a sound masking wind turbine sound, neither sound should be related to wind velocity at reference height via a (possibly implicit) neutral wind profile. In stable conditions wind induced sound on a microphone is not as loud as is usually thought (creating a high background level lowering the 'signal to noise ratio'), as in these conditions hub height wind velocities are accompanied by relatively low microphone height wind velocities. So, wind turbine sound measurements are easier when performed in a stable atmosphere, which agrees well with the night being the sensitive period for noise immission

VI STRONG WINDS BLOW UPON TALL TURBINES:

wind statistics below 200 m altitude

VI.1 Atmospheric stability in wind energy research

Atmospheric stability has a profound effect on the vertical wind profile and on atmospherical turbulence strength. Stability is determined by the net heat flux to the ground, which is a sum of incoming solar and outgoing thermal radiation, and of latent and sensible heat exchanged with the air and the subsoil. When incoming radiation dominates (clear summer days) air is heated from below and rises. Thus, thermal turbulence implies vertical air movements, preventing large variations in the vertical wind velocity gradient (*i.e.* the change in time averaged wind velocity with height). When outgoing radiation dominates (clear nights) air is cooled from below; air density will increase closer to the ground, leading to a stable configuration where vertical movements are damped. The 'decoupling' of horizontal layers of air allows a higher vertical wind velocity gradient.

In the European Wind Atlas model ('Wind Atlas Analysis and Application Program' or WAsP) [Troen *et al* 1989] wind energy available at hub height is calculated from wind velocities at lower heights. The Atlas states that "modifications of the logarithmic wind profile are often neglected in connection with wind energy, the justification being the relative unimportance of the low wind velocity range. The present model treats stability modifications as small perturb-ations to a basic neutral state." [Troen *et al* 1989]. With the growth of wind turbine heights this is now an understatement. In recent years atmospheric stability is receiving gradually more attention as a determinant in wind *energy* potential, as demonstrated by a growing number of articles on stability related wind profiles in different types of environments such as Danish offshore sites [Motta *et al* 2005], the Baltic Sea [Smedman *et al* 1996], a Spanish plateau [Pérez *et al* 2005] or the American Midwest [Smith *et al*, 2002]. Recently Archer and Jakobsen showed that wind energy potential at 80 m altitude in the contiguous US 'may be substantially greater than previously estimated' because atmospheric stability was not taken into account: on average 80-m wind velocities appear to be 1.3 – 1.7 m/s higher than assumed from 10-m extrapolated wind velocities in a neutral atmosphere [Archer *et al* 2003].

For wind turbine *noise* atmospheric stability has not been taken into account at all, leading to an underestimate of the level as well as the level fluctuations at locations and times when stability does occur. In the previous chapters this has been argued theoretically as well as demonstrated in practice for the Rhede wind farm at the Dutch-German border. The effect of increasing atmospheric stability is that higher sound levels occur more often than predicted by logarithmic extrapolation from 10 m observations, and that blade swish becomes more pronounced. The conclusion that this may be an important factor in noise annoyance is supported by a Swedish survey [Pedersen *et al* 2004].

VI.2 The Cabauw site and available data

To investigate the effect of atmospheric stability on wind, and thence on energy and sound production, data are available from the meteorological research station of the KNMI (Royal Netherlands Meteorological Institute) at Cabauw in the western part of the Netherlands. The

site is in open pasture for at least 400 m in all directions. Farther to the west the landscape is open, to the distant east are trees and low houses. More site information is given in [KNMI 2005, Van Ulden *et al* 1996]. The site is considered representative for the flat western and northern parts of the Netherlands. These in turn are part of the low-lying plain stretching from France to Sweden.
Meteorological data are available as half hour averages over several years. In the present paper data of the year 1987 are used. Wind velocity and direction are measured at 10, 20, 40, 80, 140 and 200 m altitude. Cabauw data are related to Greenwich Mean Time (GMT); in the Netherlands the highest elevation of the sun is at approximately 12:40 Dutch winter time, which is 20 minutes before 12:00 GMT.

An indirect measure for stability is Pasquill class, derived from cloud cover, wind velocity and position of sun (above or below horizon). Classes range from A (very unstable: less than 50% clouding, weak or moderate wind, sun up) to F (moderately to very stable: less than 75% clouding, weak or moderate wind, sun down). Pasquill class values have been estimated routinely at Dutch meteorological stations [KNMI 1972].

VI.3 Reference conditions

To relate the meteorological situation to wind turbine performance, an 80 m hub height wind turbine with three 40 m long blades will be used as reference for a modern 2 to 3 MW, onshore wind turbine. To calculate electrical power and sound power level, specifications of the 78 m tall Vestas V80 – 2MW wind turbine will be used. For this turbine cut-in (hub height) wind velocity is 4 m/s, and highest operational wind velocity 25 m/s. This turbine has an 'Optispeed' sound reduction possibility to reduce sound power level (by blade pitch adjustment). We will present data for the highest ('105.1dB(A)') and lowest ('101.0dB(A)') sound power curve.
Most data presented here will refer to wind velocity at the usual observation height of 10 m and at 80 m hub height. Wind shear will be presented for this height range as well as the range 40 to 140 m where the rotor is. The meteorological situation is as measured in Cabauw in 1987, where roughness height is 2 cm. The year will be divided in meteorological seasons, with spring, summer, autumn and winter beginning on the first day or April, July, October and January, respectively.

We will consider four classes of wind velocity derived from Pasquill classes A to F and shown in table 1: unstable, neutral, stable and very stable. In table 1 this is also given in terms of the shear exponent, but this is tentative as there is no fixed relation between Pasquill classification and shear exponent or stability function Ψ. This classification is in agreement with that in chapter III, though there typical mid-class values of m were given, not values at the boundaries between classes. In our reference situation 'very stable' ($m > 0.4$) corresponds to a Monin-Obukhov length $0 < L < 100$ m, 'stable' ($0.25 < m < 0.4$) refers to 100 m $< L <$ 400 m, near neutral to $|L| >$ 400 m.
This is somewhat different from the Monin-Obukhov length based classification used by Motta *et al* [2005] for a coastal/marine environment. Motta *et al* qualified $0 < L <$ 200 m as very stable, 200 m <

Table VI. 1: stability classes and shear exponent m

Pasquill class	name	shear exponent
A – B	(very – moderately) unstable	$m \leq 0.21$
C	near neutral	$0.21 < m \leq 0.25$
D – E	(slightly – moderately) stable	$0.25 < m \leq 0.4$
F	very stable	$0.4 < m$

L < 1000 m as stable and |L| > 1000 m as near-neutral, so they considered a wider range of conditions as (very) stable when compared to table 1.

VI.4 Results: wind shear and stability

VI.4.1 Height dependence of wind velocity

In figure VI.1 the average wind velocities at altitudes of 10 m to 200 m are plotted versus time of day. Each hourly average is the average over all appropriate half hours in 1987. As figure VI.1 shows, the wind velocity at 10 m follows the popular notion that wind picks up after sunrise and abates after sundown. This is obviously a 'near-ground' notion as the reverse is true at altitudes above 80 m. Figure VI.1 helps to explain why this is so: after sunrise low altitude winds are coupled to high altitude winds due to the vertical air movements caused by the developing thermal turbulence. As a result low altitude winds are accelerated by high altitude winds that in turn are slowed down. At sunset this process is reversed. In figure 1 also the wind velocity V_{80} is plotted as calculated from the measured wind velocity V_{10} with equation 3 ($z_o = 2$ cm, equivalent to equation 1 with $m = 0.14$), as well as the shear exponent m calculated with equation 1 from the measured ratio V_{80}/V_{10} ($m_{h1,h2} = \ln(V_{h2}/V_{h1})/\ln(h_2/h_1)$). The logarithmically extrapolated V_{80} approximates actual V_{80} in daytime when the shear exponent has values close to 0.14. The prediction is however very poor at night time, when m rises to a value of 0.3, indicating a stable atmosphere. For the hourly progress of wind velocities large deviations from the average wind profile occur. This is illustrated in figure 2 for a week in winter and a week in summer with measured V_{10} values and measured

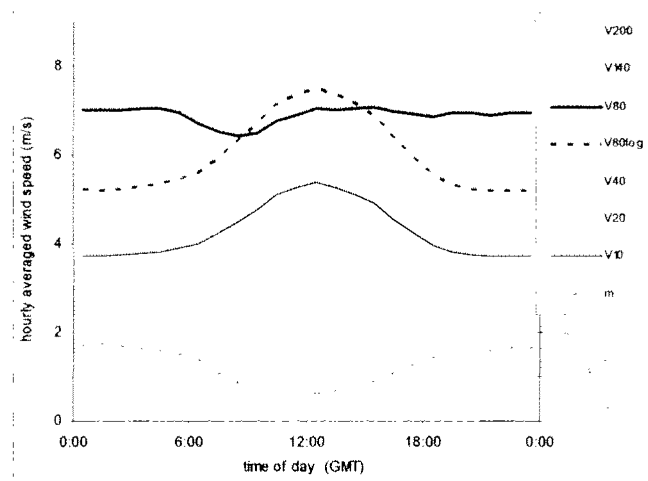

Figure VI.1: 1987 wind velocity per hour GMT at different heights 10 to 200 m (solid lines, bottom to top); logaritmically extrapolated V80 (dotted line); and shear exponent $m_{10,80}$ (+)

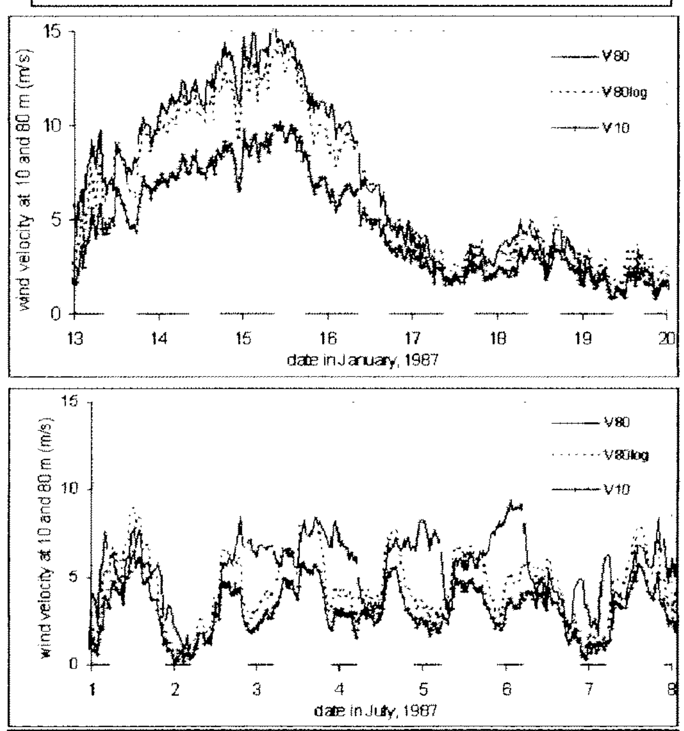

Figure VI.2: wind velocity at 10 and 80 m (solid lines), and logarith-mically extrapolated V80 (dotted line) over 7 days in January (top) and July (bottom); grey background: time when sun is down as well as logarithmically extrapolated V_{80} values. In the winter week in January 1987 ground and air were cold for a long time (below freezing point) with very little insolation. Temperature varied from night to day (diurnal minimum to maximum) with 7 °C on the first day and 5 °C or less on the next days, and the atmosphere was close to neutral with measured V_{80} more or less equal to the extrapolated V_{80}. In the summer week in July 1987 there was little clouding after the first two days; insolation was strong in daytime, and nights were 10 to 14 °C cooler than days, resulting in a stable to very stable night time atmosphere. Here, night time wind velocity was rather higher than predicted with the logarithmic wind profile.

In figure VI.3 wind velocities per hour are again plotted for different heights, as in figure 1, but now hourly averaged per meteorological season. In spring and summer differences between night and day seem more pronounced than in autumn or winter. In fall and winter, when nights are longer, wind velocities are higher.

In figure VI.4 the frequency distribution is plotted of the half-hourly wind velocities at five different heights. Also plotted is the distribution of wind velocity at 80 m as calculated from the 10-m wind velocity with the logarithmic wind profile (equation 3). Wind velocity at 80 m has a value of 7 ± 2 m/s for 50% of the time. For the logarithmically extrapolated wind velocity this is 4.5 ± 2 m/s.

In figure VI.5 the frequency distribution is plotted of the shear exponent in the meteorological seasons, determined from the half-hourly 10-m and 80-m wind velocities. It shows that, relative to autumn and winter, instability occurs more often in spring and summer whereas a neutral or mildly stable atmosphere occurs less often. A very stable atmosphere occurs more often in summer: as summer nights are short this means that a relatively high percentage of night time hours has a stable atmosphere.

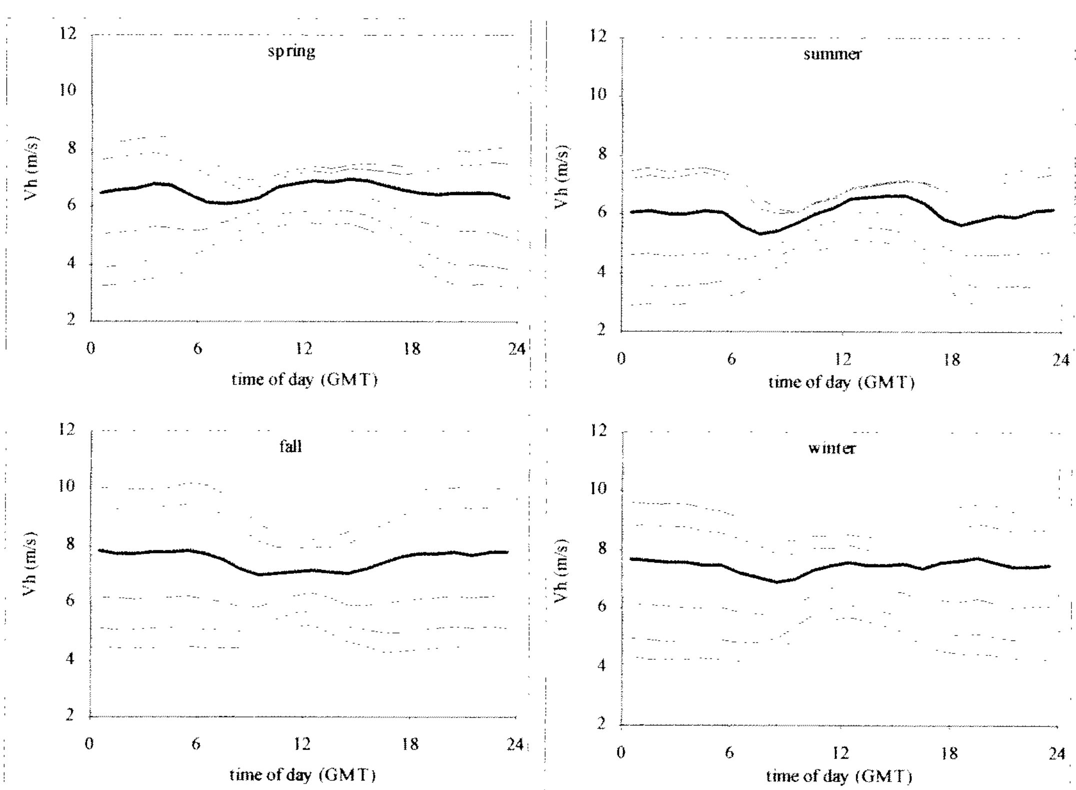

Figure VI.3: wind velocity per hour GMT at heights of 10, 20, 40, 80, 140 and 200 m (bottom to top: 80 m is bold) in the meteorological seasons in 1987