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State of the art and new perspectives for the development of noise regulation of wind farms

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Summary Wind turbine noise impacting on communities is treated differently from a country to another. While, in many cases, specific regulations do not even exist, a number of countries have developed or are in the process of developing guidelines aimed at controlling wind turbine noise.

This paper details an applied study of several regulations (USA, UK, France, Germany, Australia) against which 3 real-world wind farms with different features have been assessed. The World Health Organisation Guidelines are also considered indicatively.

The study overviews the type of noise limits defined in each regulation (fixed limit or emergence criteria), the nature of the wind farm environment, the propagation algorithm to be used and the specifics of each document.

As a result, this comparative study allows to draw attention on the pros and cons of each regulation in terms of their impacts on the community.

In the last part of the study, potential leads are discussed to ameliorate the process of assessing wind farm noise compliance for the community but also for the manufacturer and the developer/operator.

The future of wind turbines is intimately connected to its acceptance within its sound environment. Consequently, new methods to consider the wind and other influencing parameters allow new perspectives.

1. Introduction

Today, there is not a worldwide agreement on the approach to be taken in assessing wind farm noise and, when reviewing regulations, guidelines and case studies in the available literature and documentation, it is clear that there are many factors influencing the way this matter is apprehended. These can be environmental, cultural, political, financial etc. Where the problem of wind farm noise impacts has been considered, the common focus naturally is the protection of the nearby communities. It is once a compromise is sought between the local environmental impacts and the greater environmental benefits of wind energy that the assessment and handling of wind farm noise impacts become a complex undertaking.

In general, the control of noise impacts from wind farms to complying levels lies in the location and layout of the farms, by maximising distance setbacks to the nearest dwellings, and the operational management of the facilities, through the selection of the wind turbine type and the implementation of curtailment plans.

While there exists a number of publications relating the various approaches taken in the matter by different countries, this paper actually puts to the test of actual regulations and guidelines several real-world wind farms. The objective is to find out whether compliance assessment results would be different and outline the reasons for such discrepancies. It is not the point of this paper to criticise any existing legislative framework or guidelines, given each country or

institution has its reasons to adopt a view or another. However, this allows to highlight the pros and cons of such frameworks and, beyond that, provide a base to discuss new perspectives in the assessment of wind farm noise, which would benefit not only the community but also the manufacturers and developers.

In the first part of this paper, the regulatory frameworks and practice guidelines of several countries and institutions (Australia, France, Germany, UK, USA and World Health Organisation) are discussed. They are then applied to three real-world wind farms with the view to highlight the differences in compliance outcomes. Finally, on the basis of these results, the paper discusses new perspectives in the noise assessment of wind farms.

2. Legislative frameworks and practice guidelines

When reviewing the regulatory frameworks or practice guidelines applicable to wind farm noise in various countries/institutions, there basically are three main approaches considered either separately or in combination:

- A planning approach aiming at setting out distance setbacks and in-principle mitigation measures, which are non-prescriptive in terms of noise limits;
- The determination of absolute limits, which do not vary with site variables such as the evolution of background noise with wind speed;
- The determination of emergence criteria, which do consider the specificity of wind farms in that they correlate background noise and wind speed and then define noise limits against the background noise/wind speed evolution.

2.1 World Health Organisation (WHO) Guidelines for Community Noise [1] The WHO Guidelines for Community Noise tend to be applied in countries where there is no existing legislation on noise issues generally or wind farm noise more specifically. To that extent, the WHO guidelines are generic and provide guidance noise values to potential health effects. An extract of the guideline values for dwellings is presented in the Table below.

Table 1 – Guideline values for community noise in specific environments

Specific Environment	Critical health effect(s)	L_{Aeq} dB	Time base (hours)
Outdoor living area	Serious annoyance, daytime and evening	55	16
	Moderate annoyance, daytime and evening	50	16
Dwelling, indoors	Speech intelligibility and moderate annoyance, daytime and evening	35	16
	Sleep disturbance, night-time	30	8
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8

2.2 Australia In Australia, planning and approval decisions for wind farms generally rest with the various States and Territories authorities, unless a proposed facility poses a matter of national environmental significance under the Environment Protection and Biodiversity Conservation (EPBC) Act 1999 in which case approval must be sought from the Federal Government.

Below is a short discussion of the documents applied in the most populated States:

- **Victoria** Proposed wind farms are assessed under the Policy and planning guidelines for the development of wind energy facilities in Victoria [2]. These guidelines require a noise impact assessment in accordance with the New Zealand Standard NZS 6808:2010, Acoustics – Wind Farm Noise. Essentially, NZS 6808:2010 specifies noise criteria as follows.

Table 2 – NZS 6808:2010 noise limits summary

Applicable wind speed	Background sound level $L_{A90(10\ min)}$	Noise limit $L_{A90(10\ min)}$	High amenity noise limit $L_{A90(10\ min)}$
All	>35 dB	Background + 5 dB	Background + 5 dB
	30-35 dB	40 dB	
	<30 dB		35 dB

- **South Australia** Proposed wind farms are assessed under the Wind farms environmental noise guidelines [3]. In determining noise limits, this guideline refers to NZS 6808:2010 as well as research in the UK and Danish guidelines to come up with the following noise criteria.

Table 3 – South Australia noise limits summary

Applicable wind speed	Zoning	Noise limit $L_{Aeq(10\ min)}$
From cut-in to rated power wind speed	Rural living	35 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater
	Other zones	40 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater

- **New South Wales (NSW)** Noise assessment of wind farms in NSW is covered in Appendix B of the Draft NSW Planning Guidelines : Wind Farms [4]. The approach is based on that described in the South Australian guideline and NZS 6808:2010. The adopted criteria are presented in Table 4.

Table 4 – NSW noise limits summary

Applicable wind speed	Zoning	Noise limit $L_{Aeq(10\ min)}$
From cut-in to rated power wind speed	All zones	35 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater

Note that the same approach as in NSW is adopted in the State of **Queensland**, as detailed in Appendix 5 of the Draft wind farm State Code [5].
There is therefore a common trend in the noise assessment of wind farms in Australia, with slight variations in noise descriptors and absolute limits. In all cases, the daytime and night-time periods are assessed separately.

It is also worthwhile noting that the guidelines mentioned above make provisions for annoyance factors such as tonality and low frequency noise. The guidelines also share similar

methodologies for the simultaneous measurements of background noise and wind speed required to determine the applicable noise limits.

2.3 France The Order of August 26th, 2011 [6] relative to wind farms located within a facility subject to authorization under the legislation on classified installations for environmental protection is the statutory reference.

The main aspects introduced by this regulatory framework are:

- Definition of the threshold triggering the emergence criterion;
- Establishment of a tonal criterion;
- Noise limit on the perimeter of the facility;
- Compliance with the recommendations of the draft French standard NFS 31-114 in its version of July 2011.

The noise emergence is based on the difference between the A-weighted equivalent ambient noise level (including the wind turbines noise) and the residual levels.

Table 5 – Definition of noise emergence E

E = L_{Aeq} ambient – L_{Aeq} residual
E = L_{Aeq} operating wind turbines – L_{Aeq} stopped wind turbines
E = L_{Aeq} projected future state – L_{Aeq} current state (initial)

The residual level characterizes the noise level of the initial environmental features of the site, which means without any noise produced by wind turbines (noise level with stopped wind turbines).

The draft Standard NFS 31-114 Acoustic – Measurement of environmental noise with and without wind turbine activity describes the methodology to apply, taking the issues specific to wind turbines into consideration, in particular those related to noise measurements in windy environments.

The table below shows the values of maximum allowable noise emergence at the nearest dwellings. These values have to be respected for the noise levels in the emergence regulated area, when the ambient level threshold is exceeded.

Table 6 – French regulation noise limits at the nearest dwellings

Emergence regulated areas	Permitted Emergence above residual level $L_{Aeq(10\ min)}$	
	Day (7am / 10pm)	Night (10pm / 7am)
Outside For Ambient noise >35 dBA	5 dBA	3 dBA

The table below shows the values of the maximum noise level to comply with at any point of the measurement perimeter defined below:

Table 7 – French regulation noise limits on the facility perimeter

Sound level limit on the perimeter of the facility $L_{Aeq(10\ min)}$	
Day (7am / 10pm)	Night (10pm / 7am)
70 dBA	60 dBA

Measurement perimeter: Perimeter corresponding to the smallest polygon in which are comprised disks centered on each wind turbine center and radius R defined as:

R = 1.2 x (Hub height + Length of a half-rotor) in meters

In addition to the above, the French regulation makes provision for tonality.

2.4 Germany Wind farm noise impacts are assessed against the Technical Instructions on Noise Abatement (TA Lärm) [7], of which noise limits are presented below. Note that this regulation is not specific to wind farms.

Table 8 – TA Lärm noise limits for dwellings

Types of areas	Day (6am / 10pm) L_{Aeq} dB	Night (10pm / 6am) L_{Aeq} dB
Core areas, village areas and mixed-use zones	60	45
General residential areas and small residential estate areas	55	40
Purely residential areas	50	35

TA Lärm also makes provisions for tonality issues.

2.5 United Kingdom There is not any specific regulation on wind farm noise in the UK, however guidance is obtained from the research work carried out by the Working Group on Wind Turbine Noise and outlined in the ETSU-R-97 Assessment & rating of noise from wind farms [8]. The findings of this work have been further formalized for application to proposed wind farm facilities by the UK Institute of Acoustics [9]. Table 9 presents the applicable noise limits.

Table 9 – UK 'ETSU-R-97' noise limits for dwellings

Zoning	Daytime $L_{A90(10\ min)}$	Night-time $L_{A90(10\ min)}$
Residential	Background noise ($L_{A90(10\ min)}$) + 5 dB or 35 - 40dB during periods of quiet	43 dB when background noise is low, Background noise ($L_{A90(10\ min)}$) + 5 dB otherwise

Note that the night-time criterion is based on sleep disturbance, whereas the daytime criteria is based on amenity considerations.

The guide further indicates that '*where the local authority and the developer are in agreement that the background noise levels do not vary significantly between the amenity periods and the night-time, then a single lower fixed limit of 35 – 40 dBA can be imposed based upon background noise levels taken during the amenity periods and the night analyzed together*'.

The guide also describes the methodologies to adopt in the acquisition of background noise and wind speed measurements as well as the impact assessment. With regards to noise descriptors, a -2dB correction is applied to convert the L_{Aeq} sound power of the turbines into L_{A90}.

Furthermore, the guide has prescriptions for the consideration of tonality and turbine directivity. The ISO 9613-2 calculation algorithm is generally considered acceptable for the assessment of wind farm noise emissions, which is a common point with other wind farm noise guidelines mentioned previously.

2.6 USA In the USA, decisions regarding wind farm implantations rest with local Counties. There does not seem to be Federal or State specific wind farm noise policies in force. The Acoustic Ecology Institute in its Wind Farm Noise 2012 Science and policy overview [10] reviews a number of setback distances and noise limits adopted by local counties. These tend to vary significantly from a county to another, thereby reflecting the specificity of each area in

terms of demographics as well as experience and attitude to the demand in wind farm development. The common trend though is the adoption of absolute noise limits.

Professional recommendations are also available, in particular the Best practice guidelines for assessing sound emissions from proposed wind farms produced by Hessler Associates, Inc [11]. It is not clear how this document may be used in the assessment of wind farms and whether it can override the setbacks and limits adopted in the various counties but it proposes propose the following limits.

Table 10 – USA 'Best practice guidelines' noise limits for dwellings

Zoning	Acceptable $L_{Aeq\ (long\ term)}$	Maximum $L_{Aeq\ (long\ term)}$
Residential	40	45

3. Assessment of three existing wind farms

Three existing wind farms located in France and presenting different contexts have been studied against some of the noise limits discussed previously. The aim is to determine under what constraints, if any, they would be operating when subjected to noise limits used in other countries. In doing so, it should be noted that regulatory setback distances from a country to another have not been considered and that the comparison lies solely on the noise limits.

The compliance of these farms with the French regulatory framework has been established from noise measurements according to draft standard NFS 31-114 and, depending on results, curtailment plans on some or all of the wind turbines have been designed. It is acknowledged that the methodology outlined in draft standard NFS 31-114 is not rigorously similar to the methods of measurements recommended in other guidelines. However, because the measurement campaigns are thorough, they should be reasonably representative of the results that would be found under other measurement methodologies. However, a notable adjustment pertains to the noise descriptors, which are not always the same between countries. Therefore noise measurement results and calculations have been treated to take the differences in noise descriptors into account.

The following noise limits have been compared. They tend to be the lowest, therefore most stringent, in their respective guidelines/regulations. They would also correspond to substantially rural areas, which is the prominent environment of the studied wind farms.

Table 11 – Compared noise limits

Country / Institution	Descriptor	Day	Night
WHO	L_{Aeq}	50	45
Australia (NSW)	L_{Aeq}	35 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater	35 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater
France	L_{Aeq}	35 dB or background noise ($L_{Aeq(10\ min)}$) + 5 dB, whichever is the greater	35 dB or background noise ($L_{Aeq(10\ min)}$) + 3 dB, whichever is the greater
Germany	L_{Aeq}	50	35
UK	L_{A90}	35 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater	35 dB or background noise ($L_{A90(10\ min)}$) + 5 dB, whichever is the greater
USA	L_{Aeq}	40	40

The general characteristics of the 3 wind farms and the associated measurement campaigns are briefly described below.

Table 12 – Wind farm details

Wind Farm	Wind Farm 1	Wind Farm 2	Wind Farm 3
Number of wind turbines	3	6	5
Minimum distance to nearest houses (m)	540	700	710
Duration of noise monitoring campaign (days)	11	14	15
Number of measurement points/sensitive receivers considered	8/8	7/7	5/5
Type of receivers	Rural	Rural	Rural
Wind speeds covered (m/s)	4-11	3-8	4-10
Prominent wind direction (Href = 10m)	SW	SSW	SE

For consistency, all turbines on each farm have been assumed to be of the same type, and therefore subjected to the same sound power levels at full power and curtailed modes. While the wind farms developer and wind turbines manufacturers have not been named, all the calculations are based on real data.

Modelling was undertaken using CadnaA environmental noise modelling software and, in particular, the ISO 9613-2 algorithm.

Annual production losses have also been indicatively estimated. It was estimated from the electrical power outputs of the selected wind turbines for each wind speed bin and curtailed mode. The loss is calculated as the ratio of the wind farm power output with and without the curtailment plan. It takes into account a ponderation addressing the frequency of occurrence of the various wind speeds as well as the duration of the day and night periods. This estimation takes into consideration the noise constraint only.

The overall results should be taken with caution. As mentioned previously, there are differences in the methodologies in force in the various countries considered which could not be taken into account and could have influenced the findings presented below.

3.1 Wind Farm 1 The table below presents the wind turbine sound power levels at full power and curtailed modes used in the calculations.

Table 13 – Wind Farm 1 Turbine sound power levels (L_{Aeq} dBA)

Operating mode	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
Full Power	96,0	98,0	101,5	105,0	106,0	106,0	106,0	106,0	106,0
Mode 01	96,0	98,0	101,5	104,0	105,5	105,5	105,5	105,5	105,5
Mode 02	96,0	98,0	101,0	103,0	104,5	105,0	105,0	105,0	105,0
Mode 03	96,0	97,5	99,0	101,0	104,0	104,5	104,5	104,5	104,5
Mode 04	96,0	96,5	97,3	100,0	101,0	102,0	102,0	102,0	102,0

The daytime and night-time curtailment plans are shown below.

Table 14 – Wind Farm 1 Daytime curtailment plans

France									
Daytime curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power								
WTG n°2	Full Power								
WTG n°3	Full Power								

UK									
Daytime curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power								
WTG n°2	Full Power			Mode 04	Full Power				
WTG n°3	Full Power								

Australia									
Daytime curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Shutdown	Full Power	Mode 03		Mode 04	Mode 02	Full Power		
WTG n°2	Shutdown		Mode 04	Shutdown	Mode 04		Full Power		

WTG n°3	Full Power	Mode 03	Mode 04	Full Power

Germany									
Daytime curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power								
WTG n°2	Full Power								
WTG n°3	Full Power								

USA									
Daytime curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power			Mode 01	Mode 02	Mode 03			
WTG n°2	Full Power			Mode 03	Mode 04				
WTG n°3	Full Power			Mode 01		Mode 03			

WHO									
Daytime curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power								
WTG n°2	Full Power								
WTG n°3	Full Power								

Table 15 – Wind Farm 1 Night-time curtailment plans

France

Night-time curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Shutdown	Full Power	Mode 04	Shutdown	Mode 04	Full Power			
WTG n°2	Full Power	Shutdown			Mode 04		Full Power		
WTG n°3	Full Power		Mode 02	Mode 04		Mode 01	Full Power		

UK

Night-time curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Shutdown	Mode 04			Mode 02	Full Power			
WTG n°2	Full Power	Mode 04	Shutdown		Mode 04	Mode 03	Full Power		
WTG n°3	Full Power	Mode 04	Full Power	Shutdown	Mode 04	Full Power			

Australia

Night-time curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Shutdown	Full Power	Shutdown		Mode 04		Mode 02	Full Power	
WTG n°2	Full Power	Shutdown	Mode 04	Shutdown			Mode 04	Full Power	
WTG n°3	Full Power		Shutdown			Mode 04	Mode 02	Full Power	

Germany									
Night-time curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Shutdown	Mode 04			Shutdown				
WTG n°2	Full Power	Mode 04		Shutdown					
WTG n°3	Full Power		Mode 03		Mode 04				

USA									
Night-time curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power			Mode 01	Mode 02	Mode 03			
WTG n°2	Full Power			Mode 03	Mode 04				
WTG n°3	Full Power			Mode 01		Mode 03			

WHO									
Night-time curtailment plan									
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s	11 m/s
WTG n°1	Full Power								
WTG n°2	Full Power								
WTG n°3	Full Power								

Table 16 – Wind Farm 1 Estimated production loss

Country/Institution	**Estimated production loss**
France	15%
UK	14%
Australia	47%
Germany	14%
USA	5%
WHO	0%

3.2 Wind Farm 2 The table below presents the wind turbine sound power levels at full power and curtailed modes used in the calculations.

Table 17 – Wind Farm 2 Turbine sound power levels (L_{Aeq} dBA)

Operating mode	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
Full Power	87	90,7	97,5	101,9	103,5	103,5	103,5	103,5
Mode 01	87	90,7	97,5	100,9	103	103	103	103
Mode 02	87	90,7	97	99,9	102	102,5	102,5	102,5
Mode 03	87	90,2	95	97,9	101,5	102	102	102
Mode 04	87	89,2	93,3	96,9	98,5	99,5	99,5	99,5

Daytime and night-time curtailment plans are shown below.

Table 18 – Wind Farm 2 Daytime curtailment plans

France								
Daytime Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power		Mode 03	Full Power				
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power		Mode 03	Mode 04	Full Power			
WTG n°6	Full Power		Mode 03	Full Power				

UK								
Daytime Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power		Mode 03	Full Power				
WTG n°2	Full Power		Mode 04	Mode 01	Full Power			
WTG n°3	Full Power		Mode 04	Mode 02	Full Power			
WTG n°4	Full Power		Mode 03		Full Power			
WTG n°5	Full Power		Mode 03	Mode 04	Full Power			
WTG n°6	Full Power			Mode 03	Full Power			

Australia								
Daytime Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power		Mode 04	Mode 03	Mode 02	Full Power		
WTG n°2	Full Power		Shutdown	Mode 03	Mode 04	Mode 02	Full Power	
WTG n°3	Full Power		Shutdown		Mode 04		Full Power	
WTG n°4	Full Power		Shutdown		Mode 04		Mode 03	Full Power
WTG n°5	Full Power		Mode 04	Shutdown	Mode 04			Full Power
WTG n°6	Full Power			Mode 04				Full Power

Germany								
Daytime Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							
WTG n°6	Full Power							

USA								
Daytime Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power			Mode 01	Mode 02	Mode 03		
WTG n°2	Full Power			Mode 03	Mode 04			
WTG n°3	Full Power			Mode 02	Mode 04			
WTG n°4	Full Power				Mode 02	Mode 04		
WTG n°5	Full Power				Mode 03			
WTG n°6	Full Power							

WHO

Daytime Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							
WTG n°6	Full Power							

Table 19 Wind Farm 2 Night-time curtailment plans

France

Night-time Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power		Mode 04	Mode 02	Full Power			
WTG n°2	Full Power		Mode 04	Shutdown	Full Power			
WTG n°3	Full Power		Mode 04		Full Power			
WTG n°4	Full Power		Mode 03	Mode 04	Full Power			
WTG n°5	Full Power		Mode 03	Shutdown	Mode 04		Full Power	
WTG n°6	Full Power			Mode 04	Full Power			

UK

Night-time Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power		Mode 03		Full Power			
WTG n°2	Full Power		Mode 04		Full Power			
WTG n°3	Full Power		Mode 04	Mode 03	Full Power			
WTG n°4	Full Power		Mode 03	Mode 04	Full Power			
WTG n°5	Full Power		Mode 02	Shutdown	Mode 02	Full Power		
WTG n°6	Full Power			Mode 03	Full Power			

Australia

Night-time Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power		Mode 03		Mode 02	Full Power		
WTG n°2	Full Power		Shutdown		Mode 04	Full Power		
WTG n°3	Full Power		Mode 04	Shutdown	Mode 04	Full Power		
WTG n°4	Full Power		Mode 03	Shutdown		Mode 04	Mode 03	Full Power
WTG n°5	Full Power		Mode 03	Shutdown	Mode 04	Shutdown	Mode 04	Full Power
WTG n°6	Full Power			Shutdown	Mode 04	Shutdown	Mode 04	Full Power

Germany								
Night-time Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power		Mode 03	Mode 04				
WTG n°2	Full Power		Mode 04	Shutdown				
WTG n°3	Full Power		Mode 03	Mode 04	Shutdown			
WTG n°4	Full Power		Mode 02	Mode 04				
WTG n°5	Full Power			Mode 04	Shutdown			
WTG n°6	Full Power			Mode 03	Mode 04			

USA								
Night-time Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power			Mode 01	Mode 02	Mode 03		
WTG n°2	Full Power			Mode 03	Mode 04			
WTG n°3	Full Power			Mode 02	Mode 04			
WTG n°4	Full Power				Mode 02	Mode 04		
WTG n°5	Full Power				Mode 03			
WTG n°6	Full Power							

WHO

Night-time Curtailment Plan								
Standardised wind speed (Href = 10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							
WTG n°6	Full Power							

Table 20 – Wind Farm 2 Estimated production loss

Country/Institution	**Estimated production loss**
France	7%
UK	9%
Australia	26%
Germany	7%
USA	4%
WHO	0%

3.2 Wind Farm 3 The table below presents the wind turbine sound power levels at full power and curtailed modes used in the calculations.

Table 21 – Wind Farm 3 Turbine sound power levels (L_{Aeq} dBA)

Operating mode	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
Full Power	95,6	100,8	104,5	104,5	104,5	104,5	104,5	104,5
Mode 01	95,6	100,8	104,5	103,5	104,0	104,0	104,0	104,0
Mode 02	95,6	100,8	104,0	102,5	103,0	103,5	103,5	103,5
Mode 03	95,6	100,3	102,0	100,5	102,5	103,0	103,0	103,0
Mode 04	95,6	99,3	100,3	99,5	99,5	100,5	100,5	100,5

The daytime and night-time curtailment plans are shown below.

Table 22 – Wind Farm 3 Daytime curtailment plans

France								
Daytime curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

UK

Daytime curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

Australia								
Daytime curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power		Mode 03	Full Power				
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

Germany								
Daytime curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

USA								
Daytime curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

WHO

Daytime curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

Table 23 – Wind Farm 3 Night-time curtailment plans

France								
Night-time curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power		Mode 03	Full Power				
WTG n°3	Full Power		Mode 04	Full Power				
WTG n°4	Full Power		Mode 03	Full Power				
WTG n°5	Full Power	Shutdown		Mode 03	Full Power			

UK								
Night-time curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power	Mode 03	Full Power					
WTG n°2	Full Power	Mode 04	Full Power					
WTG n°3	Full Power	Mode 04	Mode 03	Full Power				
WTG n°4	Full Power	Mode 04	Mode 03	Full Power				
WTG n°5	Full Power	Mode 04	Shutdown	Mode 01	Full Power			

Australia								
Night-time curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power				Mode 02	Full Power		
WTG n°2	Full Power	Mode 04		Mode 02	Mode 03	Full Power		
WTG n°3	Full Power	Shutdown		Mode 03	Full Power			
WTG n°4	Full Power	Mode 04	Shutdown	Mode 02	Mode 04	Full Power		
WTG n°5	Full Power	Shutdown			Mode 03	Full Power		

Germany

Night-time curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power		Shutdown					

USA								
Night-time curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

WHO								
Night-time curtailment plan								
Standardised wind speed (Href=10m)	3 m/s	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
WTG n°1	Full Power							
WTG n°2	Full Power							
WTG n°3	Full Power							
WTG n°4	Full Power							
WTG n°5	Full Power							

Table 24 – Wind Farm 3 Estimated production loss

Country/Institution	**Estimated production loss**
France	7%
UK	5%
Australia (NSW)	17%
Germany	5%
USA	0%
WHO	0%

3.4 Discussion It is clear from the review of the curtailment plans that they do take different shapes even though numerically some of the noise limits may seem similar.

One influencing factor pertains to the adopted descriptors, and more specifically the comparison between wind farm noise and background noise. The UK and French approaches compare likes for likes even though the first relies on the L_{A90} and the latter on the L_{Aeq}. The resulting curtailment plans are not dissimilar and, in fact, the estimated production losses are quite close. However, when compared to Australia (NSW), which has numerically the same lower limit and shares an emergence approach with France and the UK, the curtailment plans

are much more stringent. This is due to the fact that L_{Aeq} wind farm noise is assessed against the L_{A90} residual noise, and therefore the differential is necessarily wider than when comparing the same descriptors. One would argue that, in Australia, there may not be the same siting constraints than in the more densely populated France and UK, and this is an example where the consideration of setback distances has significance.

With regards to absolute noise limits, it is interesting to see that the estimated production losses under the German guideline are nearly the same as those of France and UK even though the approach is totally different. The night-time curtailment plan for Germany tend to be more stringent, due to the 35dBA noise limit in this case, but the daytime limit is less stringent (50 dBA) therefore being less constraining for the wind farm operation.
Comparatively the curtailments under the USA advisory guideline and the WHO guidelines are the least demanding in terms of curtailment. This is in principle due to the higher limits adopted, particularly at night-time.

Finally, when comparing the curtailment plans under absolute limits and emergence criteria, the following is highlighted:

- Once the absolute limit has been reached, it appears in the examples explored in this paper that the curtailment will not further evolve with wind speed. As the wind farm noise increase with wind speed, the curtailment plan remains frozen thereby reflecting the fact that one set limit has been reached;
- In comparison, the non-linear evolution of the background noise level, regardless of descriptor, and of the turbines sound power with wind speed means that a curtailment plan can potentially be relaxed as the wind speed increases.

3. Perspectives

The concept of discomfort is closely linked to the perception that we have of its source. Once discomfort has set in, return to a healthy situation is much more complex than treating the causes upstream.

It is therefore necessary to clearly identify any methodological shortcomings related to wind farm noise and understand the issues related to wind energy from all points of view in order to establish ambitious objectives that are respectful of the environment in which wind farms must naturally fit in while fulfilling their primary function: provide an efficient renewable energy source.

3.1 Identified acoustic issues Whether through measurements or modelling, all noise aspects regarding wind farming depend upon direct or indirect factors that must be taken into account.

Uncontrolled field information/knowledge

Field information/knowledge conditions the whole value chain of a wind farm under development or in operation. Its non-scientific and non-quantifiable aspects are at the core of the perception of the acoustic engineer mission by the neighboring communities. How to establish a dialogue when several different languages are in use?
Communication from the acoustic engineer or the wind farm operator/developer with the local community must be science-based and sensitive to its perceptions. In order to resolve any noise-related issue, it is firstly needed to address a public who is identified and engaged.

Inadequate or inappropriate regulation

As outlined in the earlier parts of this paper, wind farm noise studies meet different outcomes under different regulations or guidelines used in various countries, even though the community general perception may be the same. As communities, while we are endowed with the same hearing capabilities, we would hear wind farm noise differently, thereby expressing different reactions to its perception and annoyance.

In that sense, the emergence criteria approach seems more appropriate to follow the evolution of perception than the absolute limits, which could be harshly described as a right to pollute for an energy subject to constant noise and intermittency variations.

The wind phenomenon

Regardless of absolute limits or emergence criteria, the wind is obviously an essential parameter in the assessment of wind farm noise impacts on the environment given its energy is at the core of a turbine power output.

Wind is a turbulent flow of air, consisting of a multitude of variously sized vortices, nested into each other, the smaller ones transporting the larger ones and themselves transported by the whole air movement. Wind is characterized by the following variables:

1. Its average or instantaneous speed at a given height;
2. Its average or instantaneous direction at a given height;
3. Its gradient ;
4. Its atmospheric stability class.

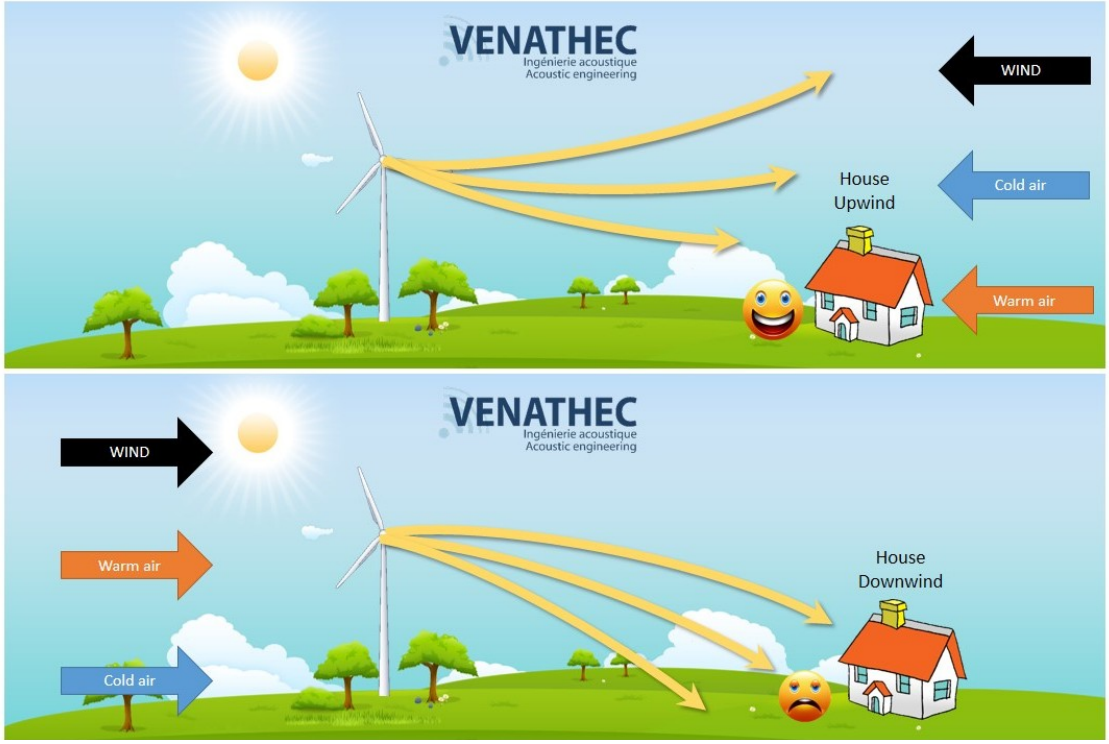
Each parameter defining the wind has an acoustic influence:

1. The contribution of individual wind turbines to the existing noise levels. Each wind turbine extracts a portion of wind energy to convert it into electricity, any wind turbine located downwind can only extract less than the upwind ones. This phenomenon, called wake, is not taken into account in noise assessments. This is equivalent to considering the least producing wind turbines as equally contributing as the most producing ones, which does not reflect reality.

2. Noise enhancement by wind as a function of wind direction can impact downwind dwellings up to 30% more compared to stationary conditions when considering the wind turbine as semi-directive. The wind shear generates sound refraction so that noise is enhanced downwind and mitigated upwind.

   Some European softwares, such as Harmonoise, allow to take occurences of wind direction into account when modelling sound propagation. This provides precious information but cannot be considered independently from other parameters. To our knowledge, no other software offers more detailed solutions in that area.

3. Wind gradient, just as the latter 2 parameters, is a consequence of field roughness which impacts both speed and direction at any height other that the hub height (measurement height). Standard values used for roughness length (often z_0=0,05 metres) lead to an error in the assessment results. Each wind turbine having a specific position on the field, it has its own acoustic properties and should therefore be independently apprehended while considering its position relative to the other wind turbines on site.



Source: VENATHEChttp://www.pa.op.dlr.de/acoustics/essay1/laerm_en.html

4. From a noise point of view, atmospheric stability is generally considered as a given. There are three parameters to reach atmospheric stability:
   - Temperature inversion;
   - Clear night with light winds.
   - Non-turbulent airflow at altitude;

   It appears in the light of these criteria that atmospheric stability is not always verified. Regulation imposing daytime and night-time measurements can lead to imprecise measurements taken in less stable or even unstable stability classes.

Measurement conditions

Each measurement campaign carried out for wind farms can vary from a few hours in some regulations to several days in others.
Any measurement is representative of the period of measurement only and merely constitutes a snapshot of the local noise climate. Measurement conditions do change during the entire life span of the wind farm.
The findings of noise impact studies are based on such snapshot and will impact the entire life span of the wind farm.

Preferably, it would be more appropriate to identify a noise annoyance when it actually occurs so as to being able to take into account the inherent environmental variations with time and avoid systematically constraining the wind turbines.

Restricted curtailment abilities

The evolution of turbine's technologies and of their control systems follow a rather slow development.
It is usual for the acoustician to provide a curtailment plan which takes into account a few parameters such as hours of the day, direction of wind and some operating modes defined by the turbine manufacturer.

A wind turbine is a compact technological aggregate controlled following two constraints : electrical and mechanical. This aggregate has not lots of freedom degrees and so provides to its customers not enough abilities to face high environmental constraints.
A more standard and efficient system of constraints calculating in real time should allow to anticipate an optimal operating mode considering both parameters : acoustics and production.

A shy feedback on maintenance and ageing

Each wind turbine is installed today with a 2 year noise warranty. Feedback on wind farming activity over the last 15 years and the corresponding noise experience allow to draw the evolution of a wind turbine in its environment with time.
Given noise issues can be directly linked to the wear or failure of electrical or mechanical parts, the acoustician expertise cannot only dwell on noise impact studies against regulations at development or commissioning stage. He must be able to get involved at all stages of the turbine life span.
With regards to the wearing of parts during the operations of wind farms, it is worth noted that noise generated by air friction on the turbine mast appears to remain steady overtime. Only two noise sources seem potentially concerned with wear: the source linked to blade rotation and the mechanical components located within the hub.
With regards to blade rotation, no significant issue has been observed in currently operating wind farms (using recent technologies) across Europe. This is mostly due to maintenance programs aimed at sustaining the turbines aerodynamic efficiency and therefore the power output of the installations.
With regards to the mechanical components within the hub, the following should be considered:

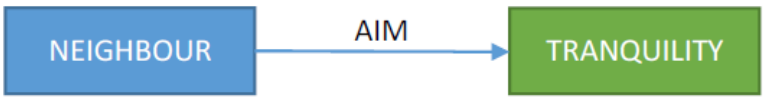
- The noise evolution of equipment is closely linked to the power output of the installation. Through maintenance programs and planned parts replacements throughout the wind farm life span, any such increase in noise levels should be negligible;
- Unlike the external part of the wind turbine, noise issues within the hub can be reduced by internal noise treatment. Such measure can be part of contractual agreements between the manufacturer and developer/operator, either after a set date (5 years) or upon warranty-based noise measurements.

3.2 Different points of view of the same situation

Whether for the development or the commissioning of a wind farm, each stakeholder has expectations of the noise impact study. Understanding these expectations must lead to being able to define a scientifically and technically optimal approach.

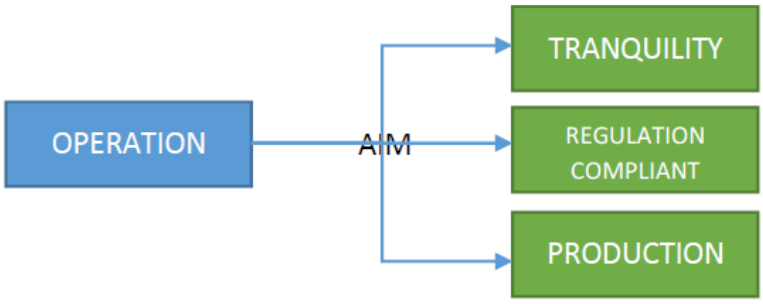
The neighbour of one or several wind farms

From the residential receiver point of view, the conservative stance of seeking to sustain a dwelling without noise annoyance is both normal and an obligation for any wind farm proposed close-by.



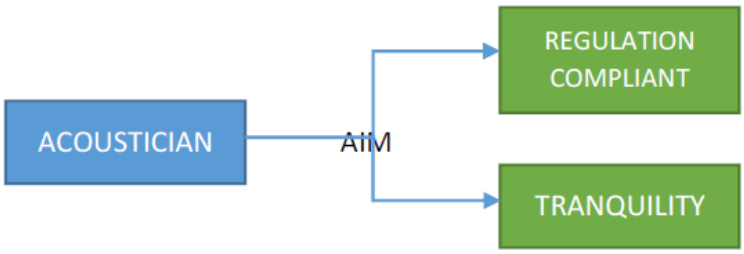
The wind farm operator

The operator seeks the efficiency of its investment within the applicable regulatory framework. Respecting its neighbours is part of the conditions to develop a site. Any complaint has more serious consequences than if the cause has been treated upstream.



The acoustic engineer

Totally independent third-party to the project, his task is to check the compliance of the wind farm and propose noise mitigation measures, if needed, to ensure compliance with the applicable noise limits.



3.3 Towards a redefined mission for the acoustic engineer

All the above considerations lead to rethinking the acoustic engineer's tasks in the wind farm noise field by taking into account issues including but also beyond noise.

A unified standpoint

The operator will tomorrow commission the acoustic engineer to ensure the tranquillity of the neighbours, not through a snapshot diagnostic but by implementing real-time noise treatment through a major technological innovation.

This innovation will require from the acoustic engineer a detailed knowledge of the production, both from the mechanical and electrical points of view. The turbine management system also requires accrued capabilities in its IT architecture and remote management of the electrical production equipment.

Using such a system, remote management of regulatory compliance provides a real-time optimisation of the field situation, and thereby of the production and noise mitigation, by not further considering the snapshot approach.

A unified regulation should allow to extend the wind turbine capabilities by imposing on manufacturers to provide extended and flexible machine control possibilities.

New technologies serving acoustics

Such technology necessitates a large research and development program, including:

- The detection, localisation et characterisation of the noise contribution of a wind turbine within the ambient noise climate ;
- The implementation of new methodologies taking into account the real-time operation of the wind turbines as a function of measured wind data;
- The implementation of a complex IT system allowing remote management of the machines;
- The retrieval, management and processing of data from the various sensors on site;
- Compatibility amongst all industrial wind turbine types;
- The implementation of a management device allowing the system to react in real-time and hence allowing the wind farm to adjust its behaviour to the wind situations encountered in real-time with regards to noise emissions.

A new, comprehensive and general competency

Therefore, tomorrow's acoustic engineer will be generalist in its approach of wind farm noise issues.

From the measurement, impact study and mitigation recommendations, his tasks will not be confined to acoustics but will include analyse, mechanical, electrical and IT skills.

His tasks will not be one-offs occurrences but aimed towards a continuous wind turbine development and optimisation to rapidly solve all the problems encountered through the life span of a wind farm.

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