WIND FARMS IN HOSTILE TERRAIN

GARRAD HASSAN & PARTNERS LTD.
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CONTENTS

ABSTRACT

The CEC has declared that a central objective of its R&D actions in the field of wind energy is to reduce the cost of wind generated electricity to 0.04 ECU/kWh or less. It is probable that this target will be first reached on sites which offer high energy density but which also bring considerable risks due to high extreme wind speeds, severe turbulence due to highly complex terrain, and conditions of icing. It is essential that these risks are properly studied and understood in order that the full potential of such hostile sites might be safely realised.

This report describes a thorough investigation of the meteorology as well as the behaviour and loading of wind turbines of different configurations at two hostile sites. The objectives of the project have been as follows:

- To understand, and hence reduce, the risks associated with the use of wind farm sites in hostile conditions;
- To provide a critical appraisal of present design procedures used for hostile environments, and to refine the design classification of wind turbines for such sites;
- To disseminate the results of the project to wind turbine manufacturers, wind farm developers, Classification Societies and Standards bodies.

In order to meet the aims of the project, measurements have been made at two wind farm sites: Windy Standard in the UK and Acqua Spruzza in Italy. In addition to detailed records of meteorological conditions, measurements have also been made of the dynamic behaviour and loading of wind turbines at the two sites. Analysis of the measured data has focused on the following topics:

- Investigation of the mean and turbulent wind speed properties over the complex topography of the Windy Standard and Acqua Spruzza sites.
- Assessment of the performance of different types of anemometry equipment and the behaviour of the monitored wind turbines during conditions of icing.
- Investigation of different techniques for the prediction of extreme wind speeds.
- Evaluation of the steady state performance and loading of the monitored wind turbines and use of the measured data to validate appropriate computer models of the machines.
- Evaluation of the fatigue and extreme loads acting on the wind turbines, correlation of these loads with the monitored wind and ice conditions, and use of the measured data to validate appropriate computer models.
- Interpretation of the measured and calculated loading of the wind turbines in order to review the adequacy of current design procedures and design standards for hostile sites.

1. PROJECT PARTNERSHIP

The project partners were as follows:

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2. OBJECTIVES

The full exploitation of the wind power potential of the European Union will require the use of complex, high wind speed and ice prone sites. The use of these sites is, at present, associated with higher risks than the more conventional sites.

The objectives of this project have been:

- To understand, and hence reduce, the risks associated with the use of wind farm sites in hostile conditions.

- To provide a critical appraisal of present design procedures used for hostile environments, and to refine the design classification of wind turbines for such sites.

- To disseminate the results of the project to wind turbine manufacturers, wind farm developers, Classification Societies and Standards bodies.

3. TECHNICAL DESCRIPTION

3.1 Background and project methodology

This report describes work carried out to investigate the risks associated with the use of wind farm sites in hostile conditions and to review present wind turbine design procedures used for hostile environments. The work has been undertaken as part of a multi-national project supported by the CEC under the Non Nuclear Energy Programme. The project, known as " *Wind Farms in Hostile Terrain*" has the contract no. JOR3-CT95-0088.

The aims of the project have been met through a combination of:

- Comprehensive measurements of environmental conditions and wind turbine loading at two "hostile"sites: Windy Standard in the UK and Acqua Spruzza in Italy.
- Detailed analysis of the measurements supported by state-of-the-art computer modelling of the environmental conditions and wind turbine behaviour.
- Assessment of the adequacy of wind turbine design standards and certification rules for hostile sites.
- Interpretation of the results of the project in the context of current design practice adopted by wind turbine manufacturers.

The project has involved the collaboration of the following organisations:

- Garrad Hassan and Partners Ltd (GH), United Kingdom,
- National Wind Power Ltd (NWP), United Kingdom
- ENEL Ricerca Polo Energie Alternative (ENEL), Italy
- Germanischer Lloyd AG (GL), Germany
- NEG Micon A/S (NEGM), Denmark

GH has had the responsibility for coordination of the project and its work has been supported by the UK Department of Trade and Industry under Agreement No. W/43/00501/00/00.

In addition to the main contractors identified above, the project has also involved the following key subcontractors:

- University of East Anglia (UEA), United Kingdom
- InterCon A/S (InterCon), Denmark
- WEST S.P.A. (WEST), Italy
- Riva Calzoni S.p.A. (RC), Italy

3.2 Measurements at Windy Standard

3.2.1 The Windy Standard wind farm

The Windy Standard wind farm is located in south-west Scotland on hills above the Carsphairn Forest, some 9km north of Carsphairn, in Dumfries and Galloway. The wind farm, which is at an average altitude of 600m, consists of 36 Nordtank wind turbines, each rated at 600kW, producing a total installed capacity of 21.6MW. The wind turbine is referred to as the NTK

600/37 throughout this report. The wind farm was constructed during 1996 and became fully operational during October of that year.

3.2.2 The NTK 600/37 wind turbine

The NTK 600/37 is a stall regulated wind turbine with a nominal power rating of 600kW. The machine is equipped with a 37.3 m diameter rotor consisting of three LM17.2 blades, each with a rotating tip brake.

The key characteristics of the turbine are tabulated below.

Designation	NTK 600/37
Manufacturer	Nordtank (now NEG Micon)
Rated power [kW]	600 (nominal)
Rotor diameter [m]	37.3
Number of blades	3
Blade material	GRP
Hub height	35
Hub type	Rigid
Rotor location	Upwind
Rotor speed [rpm]	32
Power regulation	Stall
Generator	Induction

3.2.3 Measurement systems at Windy Standard

During the course of the project there have been two measurement systems operating at Windy Standard. The wind farm supervisory control and data acquisition (SCADA) system is operated by NWP and, for the specific purposes of the *Wind Farms in Hostile Terrain* project, a scientific data acquisition system, T-MON, has been installed by GH and used to record data from the wind turbine referred to as P11 as well as additional meteorological channels from the adjacent wind farm mast.

3.2.4 The measurement programme

Data collection commenced in mid December 1996 although for the early weeks of 1997 measurements were being recorded primarily for commissioning of the T-MON system and trouble-shooting communications problems. The measurement programme for the *Wind Farms in Hostile Terrain* project began in earnest in February 1997 and was regarded as completed in July 1998.

Summary data
Some 57,000 summary data sets have been collected during the period of the measurement programme. Each summary data set contains the ten minute mean, maximum, minimum and standard deviation of all available turbine and meteorological channels.

Ten minute campaign data
A total of 561 campaign data sets has been recorded during the measurement programme. Each campaign data set contains the time history of each available turbine and meteorological channel

recorded at 40Hz over a ten minute period. In addition to manual triggering of campaign data collection, campaigns have also been triggered automatically based on a series of 22 separate trigger conditions. The trigger conditions included power production of the turbine for 2 m/s wind speed bins between cut-in and cut-out wind speeds, start-up, shutdown and emergency shutdown events, standby mode, and more extreme situations such as high turbulence (greater than 17% intensity), high yaw misalignment (greater than 30 degrees) and conditions of icing.

Meteorological campaign data
From 3rd July until 31st July 1998, measurements of the site meteorological characteristics were recorded continuously at 10 Hz. A total of 632 hours of campaign data was recorded and this has also been delivered to another Joule III Project: *Database on Wind Characteristics (JOR3-CT95-0061)*.

Hub mounted video recordings
A video camera was mounted on the hub of P11 during early December 1997. The purpose of the camera was to record ice accretion during daylight hours on one of the rotor blades over the winter months of 1997/98. The camera was therefore aligned to be able to film along the leading edge of the blade and configured to record 0.5s of film every 5 minutes. Video recordings of blade icing were made in the period from 12th December 1997 until 17th April 1998. During these months, ten separate periods of icing were identified from the recordings during daylight hours. From careful analysis of the recorded video film, three distinct types of ice formation on the blade have been identified:

- Thin sheet of ice covering large proportion of the blade surface;
- Thick, patchy ice deposits over a significant proportion of the blade surface.
- Thick crust of ice building up from the leading edge to a depth of several cm.

A comprehensive catalogue of the video recordings has been compiled.

3.3 Measurements at Acqua Spruzza

3.3.1 The Acqua Spruzza test site

The Acqua Spruzza test station has been set up by ENEL with support from the European Commission. The site is located in Italy on the Apennines, in the Commune of Frosolone, at an average altitude of 1360m.

The test station hosts eight medium size wind turbines: two WEST Medit I 320kW, two Riva Calzoni M30 200kW, two WEG MS3 300kW and two Windane 34 400kW machines.

3.3.2 The wind turbines at Acqua Spruzza

The key characteristics of the wind turbines at the Acqua Spruzza test site are tabulated below.

Designation	Medit I	M30	MS3	WD34
Manufacturer	WEST	Riva Calzoni	WEG	Vestas
Rated power [kW]	250	200	300	400
Rotor diameter [m]	33	33	33	34.8
Number of blades	3	1	2	3
Blade material	GRP	GRP + CFRP	Wood/epoxy	GRP
Hub height	26	33	25	32
Hub type	Rigid	Teetered	Teetered	Rigid
Rotor location	Upwind	Downwind	Upwind	Upwind
Rotor speed [rpm]	40	40/60	48	35
Power regulation	Pitch	Pitch	Pitch	Pitch
Generator	Induction	Two speed induction	Induction	Induction

The measurement and computer modelling work carried out during the *Wind Farms in Hostile Terrain* project has focused on the two Italian wind turbines. It should be noted that the rated power of the Medit I is actually 320kW but the demanded power was reduced to 250kW for the purposes of this project.

3.3.3 Measurement systems at Acqua Spruzza

The following measurement systems have been installed and operated at Acqua Spruzza during the course of the project:

- Measurement Control and Monitoring system (MCM)
- SQUIRREL data logger for the collection of wind statistics
- Scientific Measurement System (SMS) on one of the two M30 wind turbines
- Scientific Measurement System (SMS) on one of the two Medit I wind turbines
- SQUIRREL data logger for the collection of wind time histories
- Scientific Measurement System (SMS) on one of the two Vestas WD34 wind turbines

3.3.4 The measurement programme

Despite problems associated primarily with lightning damage of the measurement systems described above, a considerable and extremely valuable database has been established from the measurement programme at Acqua Spruzza. The nature and extent of the data collected is described below.

MCM
About five months of 10 minute summary statistics were collected from December 1995 to May 1996. After re-commissioning of the system, data was collected continuously from the end of September 1997 to mid-March 1998.

SQUIRREL data loggers
The first SQUIRREL logger operated almost continuously for more than two years collecting 10 minute average wind data.

The second SQUIRREL logger has been used to record more than 500 hours of wind time history data. In addition to the use of this data for the *Wind Farms in Hostile Terrain* project to investigate the spectral content of the turbulence, the data has also been delivered to another Joule III Project: *Database on Wind Characteristics (JOR3-CT95-0061)*.

SMS on M30
Approximately one hundred time-history data sets of 10 minutes duration were recorded in 1996 before the lightning strike which damaged the measurement system. From November 1997 the wind turbine and measurement system were both fully operational enabling collection of some 150 data sets throughout the following winter months.

SMS on Medit I
Before the lightning strike in February 1996, the SMS was able to capture a total of about 250 minutes of time history data. After the measurement system was re-commissioned in late 1997, more than two hundred 10 minute time history data sets were recorded, triggered by the wind speed monitored at hub height on mast M2.

SMS on WD34
A considerable number of time history data sets of 60 minute duration were recorded between February and April 1998. These data sets were subsequently segmented into 10 minute duration.

3.4 Wind data

3.4.1 Wind conditions at Windy Standard

The analysis of the wind conditions at Windy Standard has been based on data recorded by the various instruments on the 40m mast close to P11 over a 12 month period from August 1997 to August 1998. In addition to analysis of statistical data from the data base of ten minute summary recordings, a continuous record of time history data obtained over a period of 632 hours in July 1998 has been subjected to a detailed analysis of frequency content, gust ratios and direction changes.

An important aim of this project has been to compare in detail the environmental conditions recorded at hostile sites such as Windy Standard and Acqua Spruzza with those assumptions about environmental conditions currently recommended as the basis of wind turbine design in relevant standards and certification rules.

Although there are a number of national design standards and certification rules in use within the wind industry, the work undertaken in the *Wind Farms in Hostile Terrain* project has focused on Edition 2 of the international wind turbine design standard IEC 61400-1, recently published in early 1999 [3.4.1.1]. This standard defines a series of four wind turbine “classes” in terms of annual mean and extreme wind speeds, and the turbulence intensities. The values of the wind speeds and turbulence intensities are intended to represent the conditions at many different sites with the objective of allowing the manufacturer to design a turbine for a particular class of site conditions. The basic wind speed and turbulence parameters for the classes are tabulated overleaf.

Class		I	II	III	IV
V_{ref} (m/s)		50	42.5	37.5	30
V_{ave} (m/s)		10	8.5	7.5	6
A	I_{15} (%)	18	18	18	18
	a	2	2	2	2
B	I_{15} (%)	16	16	16	16
	A	3	3	3	3

where:

V_{ref} is the reference wind speed
V_{ave} is the annual mean wind speed
A designates the category for higher turbulence characteristics
B designates the category for lo wer turbulence characteristics

The parameter I_{15} is the characteristic value of turbulence intensity at a wind speed of 15 m/s and a is the slope parameter used to define the standard deviation of the turbulent wind speed as a function of mean hub height wind speed, V_{hub}, and I_{15}:

$$s = I_{15}(15 + aV_{hub}) / (a + 1)$$

According to IEC 61400-1, the value of I_{15} can be derived from site measurements as the mean plus one standard deviation of the distribution of 10 minute values of turbulence intensity for wind speeds greater than 10 m/s.

A comparison of the wind conditions measured at the location of the meteorological mast close to P11 on Windy Standard with those specified in IEC 61400-1 suggests that in terms of the long term annual mean wind speed and characteristic turbulence intensity, the site is well categorised as Class IIB. This finding assumes, of course, that the wind conditions at the mast location are representative of those elsewhere on the site. This assumption may not be valid since there are possibly more severe conditions at some of the more exposed locations of Windy Standard. Although the measured data does not exist to test this assumption, it is of no great importance since the conditions at the meteorological mast are reasonably representative of those at the P11 turbine, the focus of the machine loading measurement programme.

The situation regarding the extreme wind speed is not straightforward. The design standard specifies the hub height, 50 year return, extreme gust wind speed as $1.4V_{ref}$ which is equal to 59.5 m/s for Class II. Although the highest value of wind speed recorded during the 12 month measurement programme was 44 m/s, this should not, of course, be compared directly with the 50 year extreme value. It is interesting to note that according to IEC 61400-1 the one year return extreme wind speed for Class II would be 44.6 m/s but the close agreement with the highest measured wind speed of 44 m/s cannot be regarded as the basis for any valid scientific conclusion. It should also be stressed that although 44 m/s was recorded at the mast close to P11, wind speeds higher than this were recorded elsewhere on the wind farm site during the same period. It is clearly the most extreme wind speeds across a site which are relevant for a specification of environmental conditions as the basis of wind turbine design for a potential wind farm project. Various methods for the prediction of site extreme wind speeds are considered in Section 3.4.4 of this report.

Further comparison of the wind conditions at Windy Standard with the assumptions made in IEC 61400-1 has been made in the context of gust characteristics, wind direction changes and the spectral content of turbulence. A detailed analysis of the meteorological campaign data recorded over 632 hours has been undertaken for this purpose.

3.4.2 Wind conditions at Acqua Spruzza

According to long term wind measurements made at the site since 1984, the annual mean wind speed at 15 m height is close to 7 m/s. The maximum recorded 10 minute mean wind speed is 36 m/s and the maximum 10 minute mean expected with a 50 year return period is estimated to be 39 m/s. The prevailing wind directions are west-south-west and north-east.

The topography at the site and its neighbourhood is quite complex. The terrain is characterised by some wide rocky areas with steep and uneven profiles as well as undulating and smooth areas with slopes up to about 45%.

The area is mostly covered by grass, with some low bushes and rocky outcrop. Within well defined areas, some trees can also be found. The site experiences considerable snowfall and icing throughout the winter months.

Apart from the long term wind data available from the 15m wind station on the site, a substantial effort has been made during the project period to collect as much useful data as possible from the anemometry installed on the two 40 m wind masts.

The Measuring Control and Monitoring (MCM) system of the plant has collected useful wind 10 minute statistics for about five months from December 1995 to May 1996, although not continuously, and for about six months since the end of September 1997.

In addition, the SQUIRREL data logger has recorded 10 minute average wind data almost continuously for more then two years.

About 600 hours wind time series at a sampling frequency of 1 Hz have also been recorded, with the aim of investigating the spectral content of turbulence at Acqua Spruzza and at assessing how it is affected by the upwind topography.

Turbulence intensity varies with wind direction. In particular, considering the two prevailing wind directions, the wind flow appears to be on the average more turbulent when wind blows from WSW. This is clearly related to the site topography

The effect of upwind topography on vertical wind flow has been clearly monitored at Acqua Spruzza.

3.4.3 Prediction of micro-scale wind flow

A developer of a wind farm on a complex terrain site is faced with the challenging problem of determining the optimum layout of the wind turbines in order to maximise energy yield of the project whilst taking account of other possible constraints such as noise emission, electrical cable layout, roads and acceptable structural loading of the individual machines. In order to tackle this problem it is important that the developer can make use of calculation methods which will reliably model the wind flow pattern over the site topography. The most common tool used within the wind industry for modelling wind flow is WA^{s}P [3.4.3.1].

An aim of the *Wind Farms in Hostile Terrain* project has been to verify the accuracy of WA^{s}P modelling for the Windy Standard site. However, as distinct from the situation at Acqua Spruzza, it is evident that the extent of wind measurements available from different locations on the Windy Standard site prior to the construction of the wind farm is insufficient to enable a meaningful verification of a WA^{s}P model. As a consequence a different, and perhaps more directly useful approach has been adopted. In the absence of sufficient wind measurements before the construction of the wind farm, an alternative approach is to use WA^{s}P in combination with a wind turbine wake flow model to compute the wind speeds at the locations of all 36 turbines and to then compare the power output calculated on the basis of these wind speed predictions with the power output of the turbines measured by the wind farm SCADA. The accuracy of the WA^{s}P model in conjunction with wake flow modelling can then be judged in the context of the quality of the agreement between the measured and calculated power output across the wind farm. The wind farm wake model used for the study is that provided in the GH code *WindFarmer* [3.4.3.2].

The energy production for the Windy Standard wind farm has been predicted from the wind speed and direction frequency distribution corresponding to a five month period. The overall predicted and measured results show a discrepancy of 6%. The results indicate that the prediction becomes less accurate the further the turbines are from the reference mast. For those turbines near the reference mast, namely those around P11, the predictions are more accurate. The measured and predicted power output of P11 differ by some 3%. By contrast, the production of turbine G5 at the far side of the wind farm is predicted least accurately, with an error of 23%.

It is evident that in order to maximise the accuracy of predictions of energy yield from wind farms located in complex terrain, it is important that measurements from a sufficient number of masts (certainly more than one) are used to refine the site wind flow model. The uncertainty in the predictions will, of course, increase the further the turbines are located from the source of measured wind data.

3.4.4 Prediction of extreme wind speeds

The extreme wind speed at a proposed wind farm site is an important parameter for the design of the wind turbines and their foundations. It is normal practice for a wind turbine to carry a certificate of design approval issued by an internationally recognised classification society. Such design approval will have an assumed set of meteorological and environmental design parameters which include the extreme wind speed at the site. An important part of the development of a wind farm is to ensure that the predicted extreme wind speed at the proposed site is not larger than that assumed in the design of the wind turbines.

Where long high quality wind records are available from a site or a nearby meteorological station there are well developed methods for the prediction of extreme wind speed with a given return period. However, methodologies which may be used to estimate the uncertainty in a prediction are less advanced. This study has sought to investigate the uncertainty in the prediction of extreme wind speed with particular reference to short wind records.

The project partners involved in this task have been GH supported by Wind Engineering Services (WES), a UK consultant, and NWP supported by the Climatic Research Unit at the University of East Anglia (UEA). A summary of the analysis methodologies used by GH and NWP is given in the table below:

Method	GH	UEA
Classical Gumbel	✓	✓
Method of Independent storms	✓	
Peak over Threshold		✓
ESDU		✓
Simulation		✓

GH have considered data sets of 24 and 9 years recorded at Lerwick in Shetland and at the Acqua Spruzza test in Italy respectively, and wind data recorded over a six year period at Capel Cynon in Wales. The UEA analyses have been based on the data from Capel Cynon.

The methods which have been used for the prediction of extreme wind speeds are summarised below. GH and UEA have employed different variants of Modified Gumbel and Method of Storm analyses.

Classical Gumbel or Generalised Extreme Value (GEV)
The classical method for the estimation of extreme wind speeds is that derived by Gumbel [3.4.4.1]. For this method experience has shown that at least 20 years are required to obtain reliable results and the method should not be used with data sets of less than ten years. Gumbel's method is fully described in [3.4.4.2].

Gumbel's procedure is to plot the data on the standard "Type 1" axes, reduced variate y as ordinate and extreme value as abscissa, and to fit a straight line through the points. There are a number of ways to fit a straight line through the data, the most obvious being a least squares fit. However, the use of a least squares fit results in a biased estimate which is more likely to be high than low. Leiblin [3.4.4.3] has developed a method which correctly weights each of the points to ensure an unbiased result is obtained. GH have used a modified Gumbel method which allows computational calculation of appropriate weighting factors to be applied when undertaking a fit to the data points plotted on Type 1 axes. UEA use a method of probability weighted moments to achieve the same ends. UEA have also investigated a methodology which does not assume a Fisher Tippet Type 1 extreme distribution. This is referred to as Modified Gumbel $k \neq 0$ within this report.

Method of Independent Storms
Jensen and Frank [3.4.4.4] have developed a method which has been modified by Cook [3.4.4.2] to predict the extreme wind speed from "storm maxima" rather than from annual maxima. This avoids the disadvantage of the annual maxima method that much relevant data is discarded when only annual maxima are retained. Due to the retention of more extreme data points the Method of Independent Storms may be carried out using a shorter data set than that required for a Classical Gumbel analysis. Cook recommends that a minimum of seven years of data are required for an analysis using the Method of Storms whereas ten years is commonly considered the minimum for a Classical Gumbel analysis.

GH have used a modified Method of Independent Storms which allows computational calculation of appropriate weighting factors to be applied when undertaking a fit to the data points plotted on Type 1 axes.

Peak over Threshold
UEA have undertaken a Peak over Threshold (POT) or partial duration series analysis using the Generalised Pareto Distribution. This method is used in an attempt to extend the amount of data available for extreme value analysis. A range of threshold wind speeds were selected and the most appropriate value for each analysis identified.

ESDU
ESDU have proposed a method for the estimation of the extreme wind speed based on the predicted long-term Weibull parameters k and C which describe the wind speed frequency distribution at a site. This methodology is described fully in [3.4.4.5]

The advantage of this method is it can be applied to short data sets. The disadvantages are that it is assumed that the wind speed frequency distribution at a site is perfectly represented by a Weibull distribution. Additionally the relationship between the mode and dispersion of the extreme distribution is assumed to be constant for a given climatic region.

Simulation
Extreme wind speeds at a site may be predicted using a one step Markov chain model as developed by Kirchoff et al [3.4.4.6] and described by Dukes and Palutikof [3.4.4.7].

Description of the data recorded at Lerwick
A data set for Lerwick Airport spanning 24 years from 1970 to 1993 was purchased from the UK Meteorological Office. Lerwick meteorological station is situated close to the small town of Lerwick in the Shetland Islands which are located to the north of the Scottish mainland. The high wind speeds recorded at Lerwick are primarily from the west and southwest associated with the passage of frontal systems particularly in winter.

Due to high raw data costs only hourly mean wind speed data where the mean wind speed was greater than 30 knots were obtained. These data are, however, sufficient to undertake a Classical Gumbel analysis and also to apply the Method of Independent Storms. A more complete description of the data is provided in [3.4.4.2].

Description of the data recorded at Acqua Spruzza
A nine year data set for the Acqua Spruzza test site was supplied by ENEL. The Acqua Spruzza test station is located at a high, exposed location in the Apennine mountains in Central Italy. Wind speed data have been recorded using an averaging period of one hour. Data coverage over the 9 year period has generally been good, a notable exception to this was a three month period of missing data at the start of 1992. The highest wind speeds at Acqua Spruzza occur for southwesterly winds associated with the passage of frontal systems particularly in winter.

Description of the data recorded at Capel Cynon
Wind speed and direction data recorded at heights of 25, 32 and 50 m on a meteorological mast located at Capel Cynon in Wales have provided the main source of data used in the analysis undertaken by UEA. Data from this mast are available with an averaging period of ten minutes over a period of approximately six years. Data coverage rates over this period have been high. In addition data recorded at nearby locations over a period of approximately two years were available. These shorter data sets have played only a minor role in the analysis undertaken and are therefore not reported here.

The Capel Cynon site is located in rolling farmland in Dyfed in western Wales.

Development of the models used in the analysis.

A classical Gumbel analysis with an unweighted least squares fit will give a biased result which is likely to be an overprediction. To address this issue tables of Best Leiblein Unbiased Estimators (BLUE) may be used to obtain a result which is not biased. However, the BLUE method is inflexible with regard to the number of extreme values considered in a Gumbel analysis and its application is impractical for the Method of Independent Storms. WES have developed a method which allow automated calculation of parameters which permit a weighted fit to be undertaken which gives an unbiased result. Weighting factors may be calculated for any number of data points and also for a Method of Independent Storms analysis. This method is fully described in [3.4.4.8].

Apart from fitting the Type I asymptotic distribution to the data, the other task of any analysis of extreme values data requires provision of "control curves" which give an indication of the goodness of fit of the data being analysed to the target distribution, and also enables any "rogue" points to be identified. In his pioneering text Gumbel [3.4.4.1] gave procedures for providing control curves. These were based on obtaining by asymptotic methods, an estimate of the standard deviation in the neighbourhood of the mode (i.e the neighbourhood of y = 0, in terms of the standard variate y), and then assuming that the distribution in this neighbourhood is approximately normal. This allowed the construction of plus-and minus-one-sigma (standard deviation) curves, which could be entered on the Gumbel plot. Special methods were used to obtain sigma in the neighbourhood of the largest values where the asymptotic estimates were no longer valid. At the time, in the absence of electronic computation, the methods were the best available. One of the considerations of the work reported here is to show that, given powerful means of computation, it is possible to improve on Gumbel's original procedures for classical analysis of annual extremes. More recently Cook [3.4.4.2] has developed an alternative means of analysing extreme wind data which he has called "Method of Independent Storms". Derivation of suitable control curves for the storm analysis has also been undertaken within the project.

The method for deriving control curves described above provides a useful tool to the user in assessing the validity of the analysis undertaken. With experience it should be possible to define pass/fail criteria that all points should lie within a certain control curve for a valid analysis. The appropriate control curve definition which should be used for this test requires further investigation.

Conclusions and recommendations

Methods to achieve unbiased predictions of the extreme wind speed from annual maximum wind speeds have been applied by GH supported by WES and UEA working with NWP. Methods which use more of the available data have also been investigated. GH/WES have used the Method of Independent Storms while UEA/NWP have used the Peak over Threshold method using the Generalised Pareto Distribution. The ESDU method and a simulation method have also been employed by UEA.

Methods to automate the calculation of control curves for both analyses of annual maxima and storm maxima have been developed by GH/WES.

The main conclusions and recommendations from this work with regard to the prediction of extreme wind speeds at potential wind farm site are as follows:

An assessment data recorded at Lerwick on Shetland and Acqua Spruzza in Italy has been undertaken by GH/WES. The findings from this assessment are summarised below:

- For the Lerwick data of duration 24 years similar results were obtained using both the Modified Gumbel method and the Method of Independent Storms.
- Good agreement was found between GH and UEA for the predicted extreme gust wind speed at Lerwick using the Modified Gumbel method.
- A high sensitivity to the length of data set available was found. Cook [3.4.4.2] recommends that a period of at least seven years is required for a Method of Independent Storms analysis. However, results from this study indicate that significant variability appears to still be present even when seven years of data are available.
- Little sensitivity to the threshold wind speed was observed in an analysis undertaken using the Method of Independent Storms.
- The uncertainty in the predicted extreme gust wind speed estimated for a data set of 20 years duration using the method defined by WES was undertaken. It was found that the uncertainty in the prediction was approximately 10 %.

An assessment of data recorded at Capel Cynon in Wales was undertaken by UEA/NWP. The main findings are summarised below:

- Good agreement was obtained using Modified Gumbel k=0, Modified Gumbel $k \neq 0$, ESDU and Simulation methods.
- Poor agreement was obtained using the POT, when compared with the other methods.
- It was found that the POT method was sensitive to the wind speed threshold assumed.
- Confidence limits were placed on predictions made using Modified Gumbel k=0, POT and the simulation methods. The POT method is predicted to give results with the lowest confidence limits.

The uncertainty levels predicted by GH are higher than those predicted by UEA and the differences in the estimation of the confidence limits merits further investigation. However, it is clear that even when relatively long data sets are available, significant uncertainty remains in the prediction of the extreme wind speed at a wind farm site. It is therefore recommended that some conservatism is included in the definition of extreme wind speed which should be assumed in design of wind turbines and their foundations at a potential wind farm site.

3.5 Wind turbine loads

The approach adopted to investigate the loading of wind turbines sited in hostile terrain has involved the following tasks:

- Analysis of measurements from Windy Standard and Acqua Spruzza to determine the fatigue and extreme loading of the monitored turbines
- Development and validation of computer models of the monitored wind turbines
- Comparison of measured fatigue and extreme loads with those computed according to design standards

Development and validation of computer models

Computer models of the NTK 600/37, M30 and Medit I have been developed based on information supplied by the turbine manufacturers. The models have been developed for use with the GH aeroelastic code *Bladed for Windows* [3.5.1.1]. Validation of the computer models of the turbine has involved comparison of the measured and predicted data in terms of the steady state performance and loads, the modal properties of the structure, and the dynamic loading for a wide range of environmental conditions. The agreement between the measured and predicted quantities was sufficiently good to provide a satisfactory validation of the computer models.

Comparison with Standards

An important aspect of the project has been to compare the monitored fatigue and extreme loads with those predicted for the wind turbines in accordance with current design standards. This comparison is then able to indicate the degree of hostility of the Windy Standard and Acqua Spruzza environmental conditions and, perhaps more importantly, the reliability of the assumptions specified in such standards as the basis of design load calculations. The design standards considered in this exercise are IEC 61400-1 and the GL Rules and Regulations [3.5.1.2].

Fatigue loads comparison

The relevant environmental conditions required to be taken into account for fatigue load calculations are shown in the table below for Classes IA, IIA and IIB from IEC 61400-1, and Class II from the GL rules.

Classification	Annual mean wind speed [m/s]	Turbulence intensity	Air density [kg/m^3]	Upflow [deg.]
IEC IA	10.0	18% characteristic	1.225	8
IEC IIA	8.5	18% characteristic	1.225	8
IEC IIB	8.5	16% characteristic	1.225	8
GL II	8.5	20% constant	1.25	10

Environmental conditions according to GL and IEC 61400-1

Calculations of the fatigue loading of the wind turbines have been conducted based on the “classifications” shown in the table above. The calculations have involved *Bladed* simulations of the loading of the turbine for the full range of operational wind conditions. The time histories of the calculated loads have been rainflow cycle counted and the cycle counts subsequently integrated to obtain lifetime fatigue spectra.

Drawing conclusions from the results of the study is fraught with uncertainty. The two main sources of uncertainty concern firstly the predictive accuracy of the *Bladed for Windows* models of the NTK 600/37, Medit I and M30 wind turbines and secondly the reliability of the measurements. Although every effort has been made to minimise these uncertainties by means, for example, of careful calibration of measured signals and systematic validation of the turbine computer model, there must still be considerable doubt regarding the accuracy of either calculations or measurements to within the range of discrepancies between the two sets of data.

Putting aside such concerns regarding the reliability of the data, the results do appear to indicate that design calculations based on codified assumptions relating to environmental conditions may result in lower fatigue loading of certain structural components than might be experienced at a site with similar average wind speed and turbulence intensity but “hostility” of conditions in the sense of occasional severe turbulence, upflow, wind shear etc. The accommodation of perhaps infrequent but nevertheless severe environmental conditions away from the average trends seems to be potentially important for the improved reliability of design standards and calculations. At present none of the current standards provide sufficient guidance for dealing with complex terrain effects although the GL rules do require an increase of mean wind speed for turbines sited on a slope.

Extreme loads comparison

Design load cases (turbine states combined with environmental conditions) for consideration of extreme loads differ substantially across the various national and international standards available for wind turbine design. The differences are most evident with regard to the severity of environmental conditions to be considered in conjunction with failure states of the turbine, though past comparative studies have shown that similar overall maxima occur with all standards. In this study, only the fully serviceable states of the turbine have been simulated so as to provide a meaningful comparison of extreme environmental conditions alone. These environmental conditions are tabulated for the IEC 61400-1 and GL standards in the table below.

Classification	Load case	Wind speeds	Speed and direction variations
IEC	DLC 1.1	Rated and cut-out	Turbulent wind field
	DLC 1.3	Rated	Extreme coherent gust with direction change
	DLC 1.6	Rated and cut-out	Extreme 50 year operating gust
	DLC 1.8	Rated and cut-out	Extreme direction change
	DLC 1.9	Rated	Extreme coherent gust
	DLC 6.1	50 year storm	50 year storm turbulence
GL	E1.1	Rated and cut-out	Extreme combination of direction change and gust speed
	E2.1	50 year storm	50 year storm turbulence

Design load cases for extreme operational load calculations

The environmental conditions corresponding to the load cases of the IEC 61400-1 standard are dependent on turbulence intensity class.

Calculations of the extreme operational loading of the NTK 600/37 have been conducted based on the load cases required according to GL and IEC 61400-1 Class IIA and Class IIB. The extreme values of loading recorded from the P11 in power production mode are compared with the calculated data.

It is clear that the extreme operational loads calculated for the NTK 600/37 on the basis of the load cases and requirements of the GL and IEC 61400-1 standards are in general exceeded by loads recorded during the monitoring programme for this project. Although there is clearly some uncertainty with regard to the accuracy of the measured data, this result does appear to cast substantial doubt on whether the current codified requirements are sufficient for the "safe" evaluation of extreme operational loading over the lifetime of wind turbines on sites such as Windy Standard.

In the context of the structural integrity of the NTK 600/37 at Windy Standard, the above finding is not a serious cause of concern since the strength requirements of the turbine components appear to be driven by the loading associated with the non-operational rotor parked in the 50 year return storm. The 50 year return wind conditions specified for the site are in accordance with IEC 61400-1, Class I and under these conditions the extreme non-operational loads are significantly in excess of the extreme operational loads, both measured and predicted.

3.6 Impact of icing

Conditions of icing occur at both Windy Standard and Acqua Spruzza, and are particularly severe at the latter site. The measurement programmes conducted at the two sites have allowed an examination of the effects of icing on the performance of the anemometry, and the availability, performance and loading of the wind turbines at these locations. These studies are summarised in this report.

3.6.1 Influence on anemometry

A range of different types of anemometer, heated and unheated, have been installed at Windy Standard and Acqua Spruzza. An important aim of the *Wind Farms in Hostile Terrain* project has been to investigate how these various anemometers behave in conditions of icing in order that lessons can be learned for providing more reliable measurement of wind speed at such ice prone sites.

Instrumentation at Windy Standard

A summary of the instrumentation available on the meteorological mast on Polwhat Rig is presented in the table below.

Height [m]	SCADA	T-MON
35	Heated cup, heated vane and temperature	
33		Heated cup and heated vane
16.5		Heated cup and unheated cup
10	Heated cup and heated vane	
7.5		Sonic anemometer and heated cup
Base	Temperature and pressure	Temperature and ice detector

All the cup anemometers and wind vanes connected to the T-MON system were supplied by Vector Instruments and the sonic anemometer supplied by Biral. The heated anemometers were supplied with 12W of power for heating.

In addition to the instrumentation installed on the meteorological mast, each of the turbines on the wind farm is equipped with a nacelle mounted anemometer and wind vane for control purposes.

Early in the operational life of Windy Standard wind farm, it was recognised that the proprietary anemometry equipment supplied with the wind turbines did not perform well in winter conditions. The design of the wind vane, with its cone-shaped fin, was liable to fill with snow quickly, thus reducing the performance of the sensor. As part of the ongoing operational management of the wind farm, the owners have installed a number of different marques of anemometer on selected wind turbines across the site in order to assess their operational characteristics in winter conditions. Unmodified instruments have also remained in place on other machines to compare with these proprietary systems.

Instrumentation at Acqua Spruzza

Four different types of heated wind sensor have been used at Acqua Spruzza. The main characteristics of the devices are presented in the table below.

Supplier	Thies Clima	Vaisala	Rosemount Aerospace Inc.	Hydro-Tech
Country	Germany	Finland	USA	USA
Sensor type	Cup and tail vane	Cup	Vertical probe	29/04/98
Model	4.3324.21.000	WAA25	1774 W	WS-3
Operation	Optoelctronic	Opto-chopper	Diff. pressure measurement	Tachometer
Heating	Bearing only	Cups, bearing, electronics	Variable	"Cal-Rod"
Heating power	40 W	70 W total	Max 370W	Max 1500 W

It is clear from the table above that whereas the instruments supplied by Thies and Vaisala are standard 3-cup anemometers, the other devices are more unusual. The Hydrotech anemometer has a large rotor with many large cups, and the Rosemount device is a static probe which uses differential pressure measurements to determine wind speed and direction. All four instruments have been mounted on mast M1 at Acqua Spruzza. The Thies anemometer is at 33 height and the other three are located at 30m height.

Results

The specification of the anemometers installed at both Windy Standard and Acqua Spruzza included a wide variety of methods for reducing or eliminating the build-up of ice on the instruments. The experience gained from the study of these anemometers is that these methods were not as consistent or successful as their manufacturers intended.

The proprietary ice detector used in the project at Windy Standard is one of a number available on the market. The performance of the detector does not provide conclusive evidence that it would prove to be a suitably reliable device to be installed on remote, unmanned sites. Indeed, the sonic anemometer seems to have proved to be a far better, if somewhat expensive, ice detector. It is, however, not the most efficient use of such an instrument!

3.6.3 Influence on wind turbine performance

There are two main ways in which icing conditions can adversely affect wind turbine operation leading to loss of energy production:

- Through malfunction of nacelle mounted anemometry equipment which in turn causes malfunction or outage of the wind turbine;

- Through degradation of the aerodynamic efficiency of the rotor due to ice accretion on the blades.

This project has enabled these two sources of energy loss due to icing to be investigated at both Windy Standard and Acqua Spruzza. It seems clear from this investigation that loss of energy due to icing induced malfunction of control instrumentation causing turbine outage is substantially more important than energy loss due to degraded aerodynamic efficiency of the iced rotor blades.

3.6.3 Influence on structural loading

For the reasons discussed above, the main impact of icing on the wind turbines at both Windy Standard and Acqua Spruzza appears to be to cause malfunction of the control instrumentation and hence shutdown and outage. It is relatively rare for the turbines to continue to operate with icing on the blades and, furthermore, it has proven difficult to detect this when it has happened. On those occasions when it has been detected that a turbine is operating with iced blades, a systematic interpretation of the measured loads is hampered by lack of information regarding the extent of the icing present. The video camera mounted on the wind turbine at Windy Standard has assisted in this respect but even with such film recording it is very often difficult to estimate the extent of icing along the blade. In general, although there is evidence from the measurements that mean blade loading is affected by the presence of icing due to the changed aerodynamic characteristics, there is no significant evidence from the data collected at Windy Standard or Acqua Spruzza that there is a direct influence on structural fatigue loading. The most striking influence of icing on blade loads was detected on the Medit I turbine at Acqua Spruzza as a consequence of unstable pitch activity resulting from the effect of ice on the nacelle mounted anemometer.

3.7 Wind turbine design for hostile conditions

An important aim of this project is to undertake a review of the adequacy of both the design procedures adopted by manufacturers for hostile sites as well as the design rules and standards published by Classification Societies and Standards Bodies.

Before presenting comments and recommendations regarding the design procedures and standards appropriate to hostile sites, it is worthwhile to consider the question: "What is a hostile site?"

This project has been concerned primarily with the effects of a "hostile" environment on the structural integrity of wind turbines. The issue is whether a manufacturer equipped with a specification of the site environmental conditions, a recognised wind turbine design standard, and a state-of-the-art tool for predicting structural loading, is able to reliably develop a wind turbine of sufficient strength to survive for the required lifetime at the site in question. The problem for the manufacturer is, of course, even more challenging in that not only must his product have the required strength, it must also be cost-effective in order that it can compete in the market.

There are potential inadequacies in all three elements referred to above: the specification of site environmental conditions, the design standard and the tools and techniques used for load predictions may each have deficiencies affecting the reliability of design load calculations. The appropriate definition of the "hostility" of the environmental conditions in this context relates to those meteorological or site topographical effects which are not properly addressed in the site specification, design standard or load predictor. It is important to emphasise that hostility of the environmental conditions does not necessarily imply a high wind speed site, it may be much more concerned with high levels of turbulence, negative wind shear, upflow etc. By way of example, a wind turbine designed for low wind speed conditions, say IEC 61400-1 Class III, subsequently installed at a site with benign ambient wind speeds and turbulence, may experience extremely "hostile" conditions outside its design envelope if operated at close spacing from neighbouring machines within a wind farm.

In addition to consideration of hostile conditions in terms of the impact on structural loading and required component strength, another aspect of site hostility relates to potential degradation of the availability and energy yield of the wind farm. There are perhaps two main issues in this context; the effect of adverse weather conditions preventing maintenance crew reaching a remote wind farm site, and secondly, the effect of ice and/or snow degrading the energy yield of a wind turbine by inhibiting normal operation of control system instrumentation or by direct influence on the rotor aerodynamics.

3.7.1 Design practice for hostile sites

Structural design

The current approach to wind turbine design is based very largely on the concept of wind turbine classes. Design standards and certification rules will define such classes in terms of basic wind parameters. The second edition of the IEC 61400-1 standard defines a series of four wind turbine "classes" in terms of annual mean and extreme wind speeds, and the turbulence intensities. The values of the wind speeds and turbulence intensities are intended to represent the conditions at many different sites with the objective of allowing the manufacturer to design a turbine for a particular class of site conditions. The basic wind speed and turbulence parameters for the classes are as tabulated in Section 3.4.1 of this report.

It is very common for a wind turbine manufacturer to offer a series of machines, each with the same power rating but each designed for a different class. The approach to the design of such a series of machines is normally based on rotors of different diameters mounted on the same power train structural components. As the mean and extreme wind speeds increase from one class to the next, the rotor diameter is reduced in order that the fatigue and extreme loading of the power train is held constant enabling the same design to be utilised. There are many examples of this approach across the industry. The NTK 600/37 installed at Windy Standard is one design from such a series which also includes a 41m and 43m version intended for lower wind speed sites. The hub height wind conditions assumed as the basis of the design of the NTK 600/37 are compared with those assumed for the NTK 600/43 in the table below.

	NTK 600/37	**NTK 600/43**
Annual mean wind speed	9.5 m/s	8.2 m/s
Extreme gust wind speed	70.0 m/s	53.2 m/s

The current approach of a manufacturer designing a series of wind turbine variants based on the same power train components with rotor diameters appropriately tailored to develop the same fatigue and extreme loads for different classes seems on balance to be cost-effective and logical. The problem faced by a manufacturer in this approach is not with regard to uncertainty over the calculation of structural loads for different codified wind classes, but ensuring that the wind turbine variant selected for a particular wind farm project is fit to survive the actual conditions on the site for the required lifetime. Based on the results of this project it is clear that in order to minimise the risk of premature failure of a turbine, the manufacturer should assess the fatigue and extreme loading of the turbine against the environmental conditions at the site. This assessment, which will now normally be required by the wind farm developer or lender, should consider for each turbine location on the wind farm, the mean and extreme wind speeds, turbulence intensity characteristics, wind shear and upflow. Based on the worst case combination of these environmental inputs together with information regarding the local air density, the manufacturer will need to demonstrate that the fatigue and extreme loading is no more severe than that for which the machine was designed.

It is important to add that when assessing the turbulence at each turbine location on a wind farm, it is the characteristic value which must be considered for consistency with IEC 61400-1. The characteristic value turbulence is calculated as the sum of the measured standard deviation of the turbulence intensity to the mean value. Additionally, the assessment should take into account wake effects from neighbouring machines across the wind farm.

Apart from ensuring that the structural strength of a wind turbine design is adequate for the environmental conditions pertaining to a particular site, the hostility of the environment does not in itself drive the designer towards a particular configuration or particular design features. The use of structural flexibility has the potential to reduce design fatigue loading if the complexities are properly addressed. However this benefit is available and worthwhile for benign as well as hostile sites, the latter perhaps requiring greater care and "due diligence" in design analysis in order to avoid unacceptable structural displacements, vibrations etc.

Design against icing

Icing has been observed to reduce energy generation at both Windy Standard and Acqua Spruzza due to wind turbine outages, yaw misalignments, and ice accretion on the wind turbine blades. It seems clear from the measurements and observations made at both sites that loss of energy yield due to icing induced malfunction of control instrumentation causing turbine outage is substantially more important than energy loss due to degraded aerodynamic efficiency of iced rotor blades. This finding must, of course, be dependent on the severity of icing at a particular site and also, most importantly, on the extent to which the turbine control instrumentation is able to operate reliably throughout periods of icing. On the basis of the results for these two sites in this project however, there seems little justification for incorporation of heating systems within rotor blades in order to improve overall energy yield.

The complexity of the problem of operation of wind turbines on sites subject to icing is illustrated by a particular form of behaviour detected at Windy Standard. Several wind turbines were observed to operate with large yaw errors during icing periods, usually with the rotor idling and no generation taking place. This occurred due to iced wind vanes causing confused yaw activity, and iced anemometers causing the turbine controllers to inhibit yaw activity and ignore wind vane checks, in what they thought were light winds. In entering this state, the wind turbines narrowly avoided several error trips due to very unlikely combinations of wind speed, wind direction, and power which were fed to the controller. It became apparent that the response of the wind turbines during icing conditions depends on the manner in which the anemometry instruments became iced, and the prevailing wind conditions at the time. Wind turbine behaviour during icing conditions is therefore difficult to predict, and care is needed in defining control algorithms to avoid faulty operation.

It is certainly clear that the energy output of wind turbines will be reduced where they have been installed on sites subject to conditions of icing, without due consideration having been given to the adequacy of the control instrumentation and the difficulties of site access for maintenance activities.

Among the range of heaters and a surface treatment applied to the cup anemometers used at Windy Standard, none consistently performed well enough to be recommended as the panacea to the problem of ice. It has been noted that even the 70W heater on the Vaisala WAA251 was insufficient under certain conditions to keep the sensor ice-free. The performance of the Teflon coated instruments was variable but generally no better than standard instruments. Similar experiences were found at Acqua Spruzza where the two heated cup anemometers were not able to provide reliable measurements of wind speed throughout the winter months at the site.

The conditions under which ice and snow are deposited on the cup anemometers is better understood. It seems that the most significant accretion effects occur when the temperature is just above 0°C and it is likely that the precipitation is in the form of wet snow. This snow accumulates in the cups of both the anemometers and the proprietary vanes, as fitted to the turbines. The instruments then lose performance and accretion increases. If the temperature drops, the accumulated snow freezes, thus paralysing the instruments. It appears that only when the temperature then rises significantly above 0°C does the snow and ice melt and sensor operation return to normal.

Such meteorological conditions cannot, of course, be prevented. In designing wind turbines and their associated equipment to be installed in such locations, careful thought has to be given to the likely occurrence of such events. Clearly, by supplying the anemometers with significantly more heat, as with the 370W Rosemount and the 1500W Hydro-Tech devices at Acqua Spruzza, then the possibility of maintaining ice-free operation in all but the most severe of conditions increases. There are, however, implications for such a level of heat, including the supply of power, contingencies in the event of grid outages, etc.

It seems that even with a reasonable level of heat supplied to the anemometer, ice accretion can persist, if the conditions are severe enough. Wind farm developers need to be aware of the potential for down-time caused by the effects of ice and if it cannot be eradicated completely, they must make allowances for lost revenue and energy production.

At severe climate sites, the usual practice of classifying the wind regime by measuring wind speed and direction for a reasonable period needs modifying. Potential sites should be measured over a period which includes at least one winter and measurements should include wind speed, direction, temperature, relative humidity and ice accretion. If possible, further winter data should be collected or long-term data from a nearby reference station be used to assess the typical winter conditions.

The usual practice of installing such equipment in an average location for the site also needs to change. Such additional measurements as outlined above need to be carried out at the most climatologically severe location on the site so that the risk and likely severity of icing can be quantified before turbine operations begin.

3.7.2 Adequacy of design rules and standards

The design of a wind turbine involves the verification of the strength of its structural components with respect to both fatigue and extreme loads. This process involves the calculation of the fatigue and extreme loads based on the use of: a suitable computer model of the wind turbine and a series of design load cases representing the most significant design situations to be encountered by the machine. Generally the design load cases may be categorised according to the following combinations:

- Normal design situations and normal environmental conditions
- Normal design situations and extreme environmental conditions
- Fault design situations and appropriate environmental conditions
- Transportation, installation and maintenance design situations and appropriate environmental conditions

The last two above are specific to the details of the turbine design and handling procedures and are therefore of no concern to the present project. The first two categories of design load case are, however, of direct relevance to the project.

Present design standards and certification rules define the design load cases to be considered in terms of the "design situation" of the turbine and the environmental conditions. The project reported here has allowed an assessment of the adequacy of these design load cases for sites where the environmental conditions may be described as hostile as discussed above.

Fatigue load calculations

The dominant source of fatigue loading of a wind turbine is generally that associated with the power production mode. Fatigue loading is, of course, also experienced by the turbine in start-up, shutdown and standby modes although this is normally of secondary importance and is largely independent of the hostility of the environmental conditions at the site.

In the case of fatigue load calculations for the turbine in power production mode, the conventional approach is to make use of a validated aeroelastic model for simulation of the loading and behaviour of the machine operating in an adequate representation of the incident atmospheric wind flow. As discussed above, current design standards specify the parameterisation of the representation of the atmospheric wind flow for a series of design classes. By way of example, IEC 61400-1 specifies four standard classes based on the annual mean and extreme wind speeds. The standard additionally specifies the parametric values and models to be assumed for other key wind flow characteristics:

Turbulence intensity:	Class A characteristic value of 18% Class B characteristic value of 16%
Turbulence dependence on wind speed:	$s = I_{15}(15 + aV_{hub}) / (a+1)$ where the parameter I_{15} is the characteristic value of turbulence intensity at a wind speed of 15 m/s and a is the slope parameter used to define the standard deviation of the turbulent wind speed as a function of mean hub height wind speed, V_{hub}, and I_{15}:
Turbulence model:	Kaimal model Von Karman isotropic model
Wind shear power law exponent:	0.2

Air density: 1.225 kg/m^3

Upflow angle: 8 degrees

The hostility of a wind turbine design class is therefore defined in terms of the annual mean and extreme wind speeds and the characteristic turbulence. Other wind parameters are constant across the four wind classes.

Based on the measurements of wind speed and turbulence intensity made at Windy Standard and Acqua Spruzza in this project, the two sites should be categorised as Class IIB. A key concern, however, is that the measurements, particularly those at Windy Standard, have also revealed occasional ten minute periods where the meteorological parameters discussed above have values considerably removed from their averages: turbulence intensity in excess of 25%, shear exponents as diverse as -0.2 and 0.3, and upflow angles ranging from -10° to 15°. Although IEC 61400-1 requires consideration of the "characteristic" turbulence intensity (mean + one standard deviation) rather than the site average, the standard does not call on the designer to consider extreme values at the tails of the distributions of the turbulence intensity or indeed the other important meteorological parameters. The comparison of the fatigue loads measured at Windy Standard with those predicted according to the IEC standard indicates that the occurrence, albeit rather infrequent, of conditions away from the "average" codified design conditions may be responsible for a significant contribution to fatigue loading and damage.

The revision of design standards in order to accommodate the contribution of fatigue loading due to relatively infrequent periods of severe meteorological conditions is not straightforward. The problem is that the current design standards and certification rules are based on generalised classes defined on the basis of a small number of average or, in the case of turbulence, characteristic values. Enhancement of the standards would require information about the probability distributions of such meteorological parameters as turbulence intensity, wind shear, upflow etc. which is site-specific and not easily generalised. A partial improvement would be to ensure that the standard incorporates appropriate guidance relating to the "assessment of external conditions" in order to verify that the design assumptions are "safe" with respect to the conditions within a particular wind farm at a particular site. The development of reliable guidance in this context will require further research effort and will form an important element of the third revision of IEC 1400-1 which will commence in late 1999.

Extreme load calculations

From the results obtained in this project, it is clear that the extreme operational loads calculated on the basis of the IEC 61400-1 are not conservative relative to those measured for the NTK 600/37 at Windy Standard and the M30 and Medit I at Acqua Spruzza. Although, as has been stated elsewhere in this report, there is uncertainty regarding the accuracy of both the measured and predicted loads, there does appear to be considerable evidence that the calculation of extreme wind turbine loading on the basis of deterministic wind speed gusts and direction changes and wind shear transients is not satisfactory. The form, amplitude and time period of such codified discrete wind conditions remain rather arbitrary and it seems clear that the development of more reliable methods of extreme load prediction, most likely based on probabilistic techniques, is necessary.

4. RESULTS AND CONCLUSIONS

The results and conclusions of the project are presented below. It should be emphasised that the work undertaken has aimed at investigating the risks associated with the use of wind farm sites in hostile conditions. The main results and conclusions of the project are therefore somewhat intangible being the knowledge gained with regard to the problems of hostile terrain wind farms. Although intangible, the results and conclusions are nonetheless valuable in terms of the insight they provide to wind turbine manufacturers, wind farm developers, Classification Societies and standards bodies concerned with wind power technology.

The results and conclusions of the project are owned jointly by the consortium of organisations involved with the programme of work:. It is intended, however, that the information be disseminated widely throughout the wind industry. The results and conclusions are as follows:

- Large databases of environmental and wind turbine loading measurements have been established from the work conducted at both Windy Standard and Acqua Spruzza. The installation, commissioning, continuous operation and repair of sophisticated monitoring equipment at hostile locations such as Windy Standard and Acqua Spruzza has, nonetheless, proved to be a significant challenge in itself. Problems have occurred at both sites ranging from atrocious weather hindering the final installation and commissioning of the T-MON system at Windy Standard, to severe damage of the Scientific Measurement Systems at Acqua Spruzza as a result of lightning damage. Lightning strikes occur frequently at Acqua Spruzza and despite ENEL having incorporated specifically designed protection systems, lightning has necessitated an extensive and costly maintenance activity throughout the project. The difficulties and costs of undertaking measurements at such sites should not be under-estimated in future projects.

- An important aim of this project has been to compare in detail the environmental conditions recorded at hostile sites such as Windy Standard and Acqua Spruzza with those assumptions about environmental conditions currently recommended as the basis of wind turbine design in relevant standards and certification rules. It seems clear from the analysis of the wind measurements at Windy Standard that the long term, average meteorological conditions are no more severe than as specified for a Class IIB site, in accordance with IEC 61400-1. Based on these average conditions Windy Standard should not be categorised as a "hostile" site. This finding assumes, however, that the wind conditions at the mast location are representative of those elsewhere on the site. This assumption may not be valid since there are possibly more severe conditions at some of the more exposed locations of Windy Standard. It is clearly the most extreme wind speeds across a site which are relevant for a specification of environmental conditions as the basis of wind turbine design for a potential wind farm project.

  A further concern, however, is that the measurements have also revealed occasional ten minute periods where the meteorological parameters discussed above have values considerably removed from their averages: turbulence intensity in excess of 25%, shear exponents as diverse as -0.2 and 0.3, and upflow angles ranging from -10° to 15°. For the normal wind turbine classes defined in IEC 61400-1, the standard does not call on the designer to consider such extreme values at the tails of the distributions of these meteorological parameters.

- Analysis of the wind conditions recorded in the project has indicated that the largest values of gust factors derived from the measured data are significantly lower than the "extreme operational gust" (EOG) data from IEC 61400-1, but in excess of the results obtained from the "extreme coherent gust" (ECG). This latter result is perhaps not too suprising since the ECG, by definition, is assumed to be "coherent" over the rotor disk and its comparison with "single point" data from an anemometer is therefore unreasonable. The results appear to indicate that wind direction changes specified in the standard are generally less than those extrapolated from the measured data. In the case of the "extreme coherent gust with direction change" (ECD) this is not unexpected since, as was the case with the ECG, the condition is assumed to be fully coherent over the rotor disk and comparison with the direction change recorded by a wind vane is not reasonable. The comparison of the measured data with the "extreme direction change" EDC is, however, valid in the context of spatial dimensions and the results, taken at face value, do appear to suggest that the standard may not be sufficiently severe.

- An aim of the project has been to verify the accuracy of WAsP modelling for complex terrain sites. In the absence of sufficient wind measurements from Windy Standard before the construction of the wind farm, an alternative approach to this verification has been undertaken. The approach has involved the use of WAsP in combination with the GH wind turbine wake flow model, *WindFarmer*, to compute the wind speeds at the locations of all 36 turbines and to then compare the power output calculated on the basis of these wind speed predictions with the power output of the turbines measured by the wind farm SCADA.

  The overall predicted and measured energy output of the wind farm differed by some 6%. The results indicated, rather unsurprisingly, that the predicted power output became less accurate the further the turbines are from the reference mast. It is evident that in order to maximise the accuracy of predictions of energy yield from wind farms located in complex terrain, it is important that measurements from a sufficient number of masts (certainly more than one) are used to refine the site wind flow model. The uncertainty in the predictions will, of course, increase the further the turbines are located from the source of measured wind data.

- The project has involved a study of the prediction of extreme wind speeds with particular reference to short measured data sets. It is clear from the study that across the range of techniques considered, there remains significant uncertainty in the prediction of extreme wind speeds even when relatively long data sets are available. It is therefore recommended that some conservatism is included in the definition of extreme wind speed to be used as the basis of the design of wind turbines and foundations at potential wind farm sites.

- Conditions of icing occur at both Windy Standard and Acqua Spruzza, and are particularly severe at the latter site. The measurement programmes conducted at the two sites have allowed an examination of the effects of icing on the performance of the anemometry, and the availability, performance and loading of the wind turbines at these locations.

  The specifications of anemometers installed at both Windy Standard and Acqua Spruzza included a wide variety of methods for supposedly reducing or eliminating the build-up of ice on the instruments, thus maintaining sensor performance. The results obtained in this project have suggested that these methods were not as consistent or successful as their manufacturers intended.

There are two main ways in which icing conditions can adversely affect wind turbine operation leading to loss of energy production:

- Through malfunction of nacelle mounted anemometry equipment which in turn causes malfunction or outage of the wind turbine;
- Through degradation of the aerodynamic efficiency of the rotor due to ice accretion on the blades.

It seems clear from the measurements and observations made at both sites that loss of energy yield due to icing induced malfunction of control instrumentation causing turbine outage is substantially more important than energy loss due to degraded aerodynamic efficiency of iced rotor blades. This finding must, of course, be dependent on the severity of icing at a particular site and also, most importantly, on the extent to which the turbine control instrumentation is able to operate reliably throughout periods of icing. It is certainly clear that the energy output of wind turbines will be reduced where they have been installed on sites subject to conditions of icing, without due consideration having been given to the adequacy of the control instrumentation and the difficulties of site access for maintenance activities.

For the reasons discussed above, the main impact of icing on the wind turbines at both Windy Standard and Acqua Spruzza appears to be to cause malfunction of the control instrumentation and hence shutdown and outage. It is relatively rare for the turbines to continue to operate with icing on the blades and, furthermore, it has proven difficult to detect this when it has happened. On those occasions when it has been detected that a turbine is operating with iced blades, a systematic interpretation of the measured loads is hampered by lack of information regarding the extent of the icing present. The video camera mounted on the wind turbine at Windy Standard has assisted in this respect but even with such film recording it is very often difficult to estimate the extent of icing along the blade. In general, although there is evidence from the measurements that mean blade loading is affected by the presence of icing due to the changed aerodynamic characteristics, there is no significant evidence from the data collected at Windy Standard or Acqua Spruzza that there is a direct influence on structural fatigue loading. The most striking influence of icing on blade loads was detected on the Medit I turbine at Acqua Spruzza as a consequence of unstable pitch activity resulting from the effect of ice on the nacelle mounted anemometer.

- This project has been concerned primarily with the effects of a “hostile” environment on the structural integrity of wind turbines. The issue is whether a manufacturer equipped with a specification of the site environmental conditions, a recognised wind turbine design standard, and a state-of-the-art tool for predicting structural loading, is able to reliably develop a wind turbine of sufficient strength to survive for the required lifetime at the site in question. The problem for the manufacturer is, of course, even more challenging in that not only must his product have the required strength, it must also be cost-effective in order that it can compete in the market.

Based on the measurements of wind speed and turbulence intensity made at Windy Standard and Acqua Spruzza in this project, the two sites might be considered as rather benign and should be categorised as Class IIB according to IEC 61400-1, Edition 2. As stated above, a key concern, however, is that the measurements, particularly those at Windy Standard, have also revealed occasional ten minute periods where the important meteorological parameters have values considerably removed from their averages. Although

IEC 61400-1 requires consideration of the "characteristic" turbulence intensity (mean + one standard deviation) rather than the site average, the standard does not call on the designer to consider extreme values at the tails of the distributions of the turbulence intensity or indeed other key meteorological parameters such as wind shear, upflow, etc. The comparison of the fatigue loads measured at Windy Standard with those predicted according to the IEC standard (refer Section 3.5.1.4) indicates that the occ urrence, albeit rather infrequent, of conditions away from the "average" codified design conditions may be responsible for a significant contribution to fatigue loading and damage.

The revision of design standards in order to accommodate the contribution of fatigue loading due to relatively infrequent periods of severe meteorological conditions is not straightforward. The problem is that the current design standards and certification rules are based on generalised classes defined on the basis of a small number of average or, in the case of turbulence, characteristic values. Enhancement of the standards would require information about the probability distributions of such meteorological parameters as turbulence intensity, wind shear, upflow etc. which is site-specific and not easily generalised. A partial improvement would be to ensure that the standard incorporates appropriate guidance relating to the "assessment of external conditions" in order to verify that the design assumptions are "safe" with respect to the conditions within a particular wind farm at a particular site. The development of reliable guidance in this context will require further research effort and should form an important element of the third revision of IEC 61400-1 which will commence in late 1999.

It is also clear from the work undertaken in the project that the extreme operational loads calculated on the basis of the IEC 61400-1 are not conservative relative to those measured for the NTK 600/37 at Windy Standard and the M30 and Medit I at Acqua Spruzza. Although, as has been stated elsewhere in this report, there is uncertainty regarding the accuracy of both the measured and predicted loads, there does appear to be considerable evidence that the calculation of extreme wind turbine loading on the basis of deterministic wind speed gusts and direction changes and wind shear transients is not satisfactory. The form, amplitude and time period of such codified discrete wind conditions remain rather arbitrary and it seems clear that the development of more reliable methods of extreme load prediction, based on probabilistic analysis, is crucially important in order to improve confidence in such design calculations.

5. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

This project has provided the first set of detailed results from wind turbines operating in extreme wind and ice conditions and high turbulence in complex terrain. The results will be fed directly to manufacturers to enable them to improve their machine designs, to wind farm developers to enable them to assess the risks of using hostile sites and to Standards bodies and Classification Societies to improve the design rules.

The results will not be exploited by the project partnership as an entity but rather by the constituent partners all of whom have a direct interest in having a better understanding of wind farms in hostile terrain.

NWP and ENEL will both continue to be involved in the development of wind farms in such conditions, NEG Micon will supply machines to such developments. GL will improve as appropriate its rules and regulations as a result of the experiences of this project and hence disseminate the findings widely throughout the wind energy industry. The same task will be undertaken by GH through its commercial links with many of the manufacturers and developers in the EU as well as directly through participation in standards committees and certification work.

The overall anticipated benefit of the work describe in this report lies in the improved understanding of the behaviour and loading of wind turbines operating at hostile terrain sites. This improved understanding should allow the problems brought by such sites to be tackled with a greater degree of confidence, allowing a reduction of risk in order that the full potential of hostile terrain sites might be safely realised.

6. POTENTIAL APPLICATION

The work undertaken in this project has been aimed at understanding, and hence reducing, the risks associated with the use of wind farm sites in hostile conditions. The results obtained will assist wind turbine manufacturers and wind farm developers to deal more confidently with complex, high wind speed and ice prone sites such as that associated with the Windy Standard wind farm shown overleaf.

Windy Standard Wind Farm
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