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WIND ENERGY PRODUCTION IN COLD CLIMATE (WECO)

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WECO
Wind **E**nergy in **Co**ld Climate

1 SUMMARY

This report introduces main results and recommendations of the research project "**W**ind **E**nergy Production in **CO**ld climates" **WECO (JOR3-CT95-0014),** which was partially supported by the European Commission DG XII Non Nuclear Energy Programme aiming at the investigation of wind turbines under cold climate operation.

It is shown experimentally and by numerical simulations that icing of rotor blades or other components lead to decreased production due to ice accretion or safety demands. The icing effect is directly related to the climate of the site of the wind turbine, and varies strongly from region to region in Europe. Extreme low air temperature again arises new demands for design parameters. Icing of anemometers and other wind gauges typically lead to wrong estimation of wind power potential and operational problems of wind turbines.

The icing map over Europe, based on meteorological observations from 120 synoptic stations, show that icing and cold weather conditions occur in large regions in Europe, not only in the Nordic countries but also especially at mountainous regions in Northern Europe, Germany, UK, Alps, Spain and central Italy. On the other hand new megawatt turbines are high enough to encounter in-cloud icing even in lowlands. Following the method used to construct the European wind atlas, icing data is presented to show how it affects on-site wind power production.

Experimental data, wind tunnel simulations and numerical analyses were used to describe the ice formation on wind turbine blades, to produce the C_l, C_d values, to calculate the power curves for iced wind turbines, and to study the loads. Ice on blades usually decreases the power production. At harsh sites the annual power loss may be up to 20-50 %. The project also produced a preliminary method to combine the European Wind Atlas method, iced power curves and statistics of in-cloud icing to estimate annual or monthly losses due to icing at desired site.

For environmental safety icing is a significant design parameter. New theoretical study in ice throw from the rotating blades was verified to observations. As preliminary results it is recommended that for sites with high probability of icing (1) to keep distance 1.5 (hub height + rotor diameter) between the turbines and nearest objects, and (2) to stop the turbines during the icing period and wind coming from unfavourable directions.

Conventional and ice-free anemometers were tested at several sites in Europe. It was shown that at ice en-dangered sites ice-free anemometers have to be used to avoid measurement errors of wind speed. Due to use of non heated anemometers the wind potential is now underestimated at many regions in Europe. Icing of anemometers also lead to false operation of wind turbines causing losses in power production. Thus it is recommended that all wind turbines operating under cold weather conditions ought to be equipped with ice free wind gauges. Turbines sited in mountains and in the far north have to have very strongly heated wind gauges. The intercomparisons and the market survey showed that there are some ice free gauges suitable for sites with less heavy icing are available today, but there is a need to produce accurate and reliable anemometers for heavily iced regions.
Keywords: Wind turbines, icing, low temperature, load, power production, ice-free anemometers

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3 INTRODUCTION

Cold climate has not been a factor which has been taken into account in details in the planning and operation of wind turbines. Until the very latest years the wind turbines have been mainly erected on coastal sites in less hostile environments, where air temperature far below freezing point, freezing rain or in-cloud icing forming strong ice cover on the structures or even sea ice do not occur or they have very marginal importance as design parameters.

However, there is a growing and identified interest to erect more wind turbines at sites affected even by heavy icing conditions in various parts of Europe, like mountainous regions in Northern Europe, Germany, UK, Alps and central Italy. It is estimated [13] that about 20 per cent of the installed wind power (8000 MW by the year 2010) is going to be realised at sites were icing has to be taken into account in order to utilise the existing wind energy potential in Europe. The EU/JOULE3 WECO (**W**ind **E**nergy Production in **CO**ld Climates) project addressed many of the questions connected to the problems expected and produced information and recommendations to assist in the exploitation of cold climate sites [16], [17].

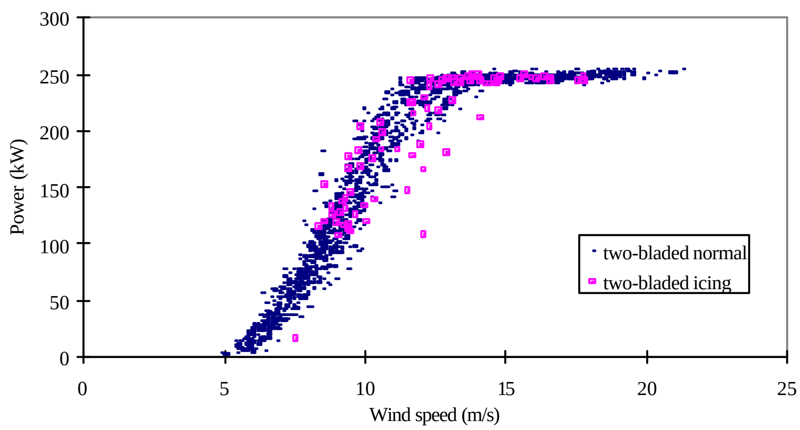
Icing of rotor blades (Figure 1) or other components (Figure 2) of wind turbines (WT) may lead among other things to decreased power production (Figure 3, Figure 4), increased ultimate and fatigue loads, or long stops without production either due to heavy icing or safety demands due to possibility of ice throw. Light clear ice on the blade and low air temperature (high air density) can also lead to temporary overproduction by the wind turbine. Together with high risk in predicting the wind potential at cold climate sites, these effects can strongly diminish the economics of wind energy projects.

The WECO project studied in-cloud icing, icing of WTs and icing effects on loads and power production by taking experimental data from several test sites at various locations in Europe, using numerical codes and wind tunnel simulations, intercomparisons, questionnaires sent to operators and manufacturers, market surveys and international public seminars to discuss the problems, experience and achievements.

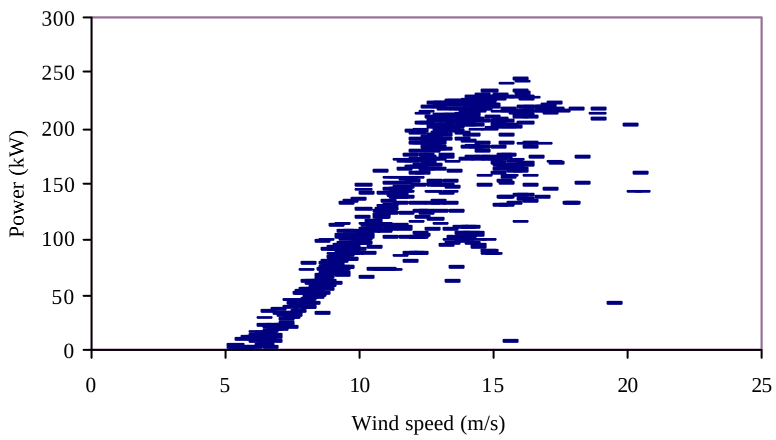
The WECO project produced about 90 papers, in which the results and remaining problems are discussed in details. In this paper the results are summarised very briefly.

Figure 1. An example of extremely iced leading edge of a rotor blade in Germany (Photo: Kranz, in[1], left side).

Figure 2. Iced leading edges and anemometer on a 150 kW wind turbine in Switzerland [14],[22], (right side).



a)



b)

Figure 3. Measured power curves during winter time at a) Acqua Spruzza, Italy, where icing is observed from November to March, a slight icing case shown in the figures was recorded in November-December, 1997 at Medit two bladed turbines. b) The Pyhätunturi test site in northern Finland during winter months 1996 with iced rotor blade [10] for a 220 kW Wind World turbine.

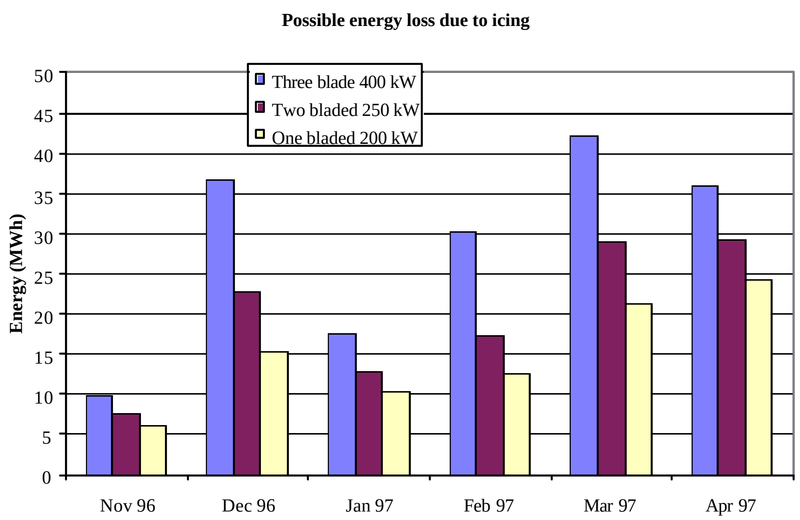


Figure 4. Possible average annual energy loss (MWh) for turbines due to icing conditions [31].

4 OBJECTIVES

The main objectives of the WECO project were as briefly described:

- To produce a method for wind energy assessment based on Wind Atlas Method and the ”Icing map” data over Europe
- Improvement and verification of models and methods used to estimate loads, reduction of power output and lifetime under different types of icing conditions
- To verify and improve prediction of aerodynamics of iced blades using e.g. wind tunnel investigation of iced airfoils and their influence on loads and power production.
- Develop guidelines for design of blade heating systems
- Give recommendations to increase safety for operation of WT under icing conditions
- Testing of ice-free anemometers for improved wind potential prediction and for the use as control instruments of wind turbines and a market survey in ice-free wind gauges.
- Market survey and field test of ice detectors.
- Evaluation of experimental data from wind turbines operating under icing conditions from sites in Finland, Estonia, Germany, UK, Switzerland and Italy.
- Evaluation of an inquiry on effect of icing in various parts of Europe.
- Transfer of results to industry, operators, certification bodies, and public administration by seminars, publications and personal contacts.

5 TECHNICAL DESCRIPTION AND RESULTS

WECO was a large multifarious research project covering and investigating various subjects and thus, only some key results are introduced and highlighted in the following.

5.1 Icing map

To be able to estimate to effect of icing on annual power production and loads, the type, frequency and duration of icing events and corresponding wind speeds are essential parameters to be known.

The meteorological data have been collected from the test stations within the project and from existing meteorological databases and have been analysed in order to develop an icing map for Europe. Therefore meteorological data from 120 meteorological official weather stations in Europe in cooperation with the EUMETNET SWS project [15] have been evaluated resulting in the number of icing days, calculated rime accretion at various altitudes [4], [9] and the estimated power loss for typical wind turbines.

Freezing rain for example may lead to increased roughness of the blade (if the event occurs during stand still) and reduced the power production when taken into operation, or even over production due to increased chord length of the blade (if icing occurs during operation). Freezing rain is normally recorded at the meteorological stations, and the statistics can thus be taken into account when planning the wind power plant.

However, the most severe icing is caused by in-cloud icing, which is typical for hilly and mountainous regions, when super cooled cloud droplets collide with a cold surface. The mass of ice collected on the surfaces depend on the liquid water content in the air flow, the collision efficiency of the droplets, wind speed (or tangential speed of the blade element), the area of the cross section of the structure, air temperature and time. The rate of atmospheric icing is poorly observed and practically not at all measured. Thus there are not data available of this phenomena.

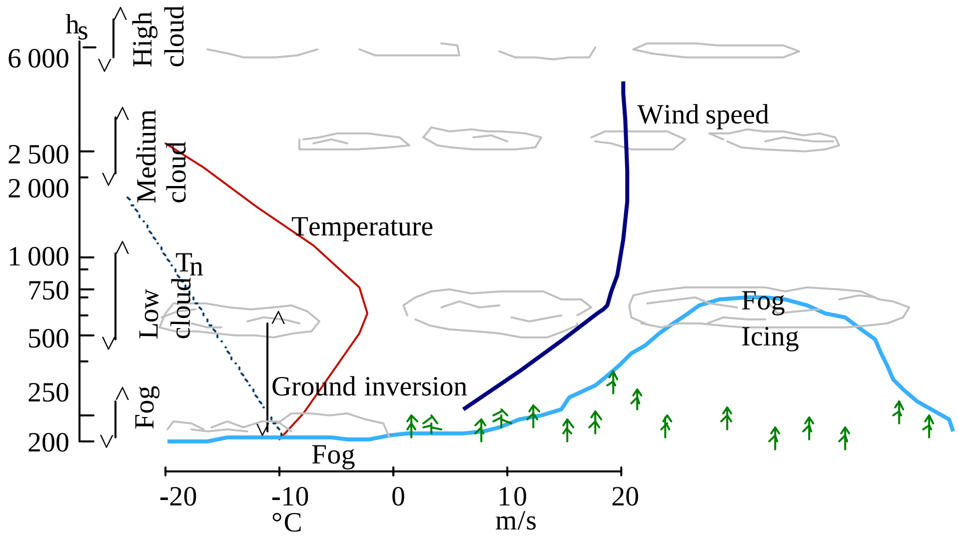


Figure 5. A schematic description of in-cloud icing upon the summit of a hill, while no icing is observed at the nearby lowlands or on the slopes of the hill [4], [9]*. No icing occur at altitudes between the Low clouds and Medium height clouds.*

It is recommended for the wind energy site evaluation and wind farm planning to combine the icing map data with the European Wind Atlas for better prediction of energy production taking the icing effect into account at various cold climate areas in Europe. The icing map and the data base in the background, developed in the WECO project is a first step to help wind farm developers to better planning of their projects in ice endangered areas and thus, improve the prediction of the economics.

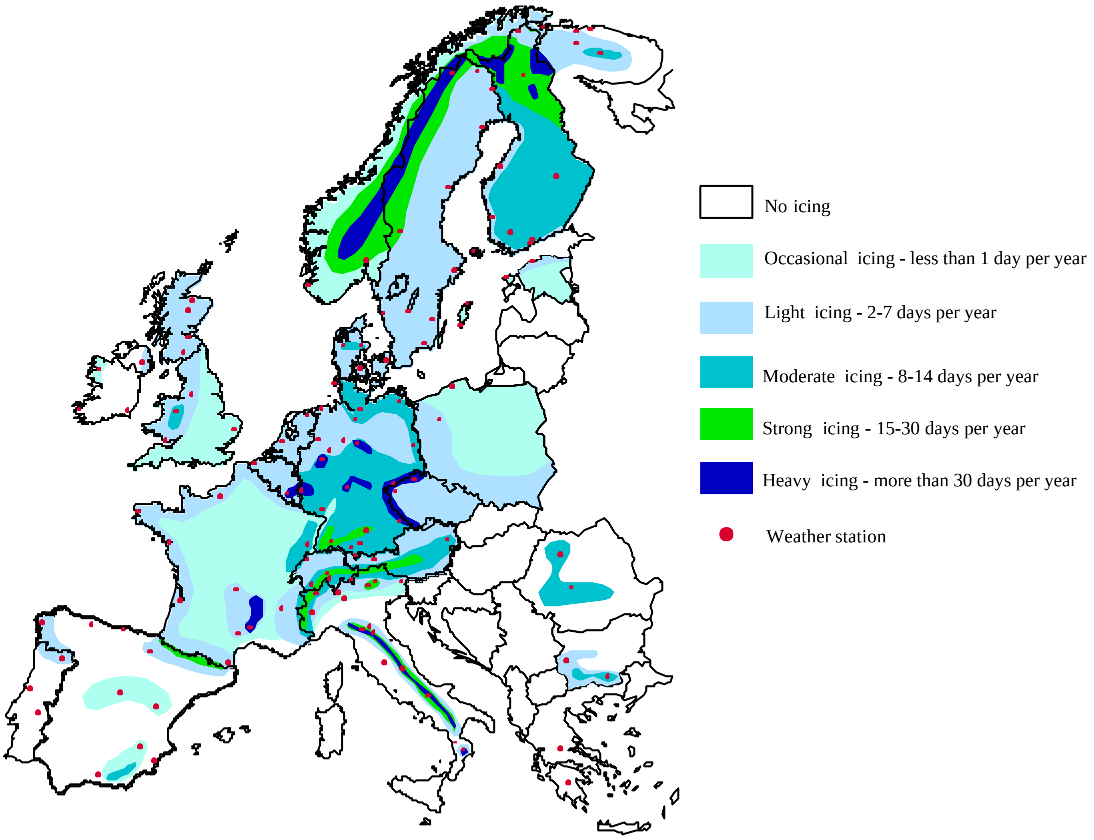


Figure 6. Distribution of the number of icing days in Europe, when the average annual number of icing days is calculated for in-cloud icing for the meteorological observation stations marked with red dot. Data 1991-1996 [15], [18].

The rate of rime accretion during in-cloud icing was estimated by the empirical formula based on the measurements performed at the Pyhätunturi test site in northern Lapland. Due to the use of ice free anemometers to measure the velocity of the air and the mass flow of the droplets the parameters in the empirical equation differs significantly from those used earlier e.g. in Finland [10].

As seen from the observations and measurements carried out within the WECO project, icing occurs at very large areas in Europe. The number of icing days and the amount of rime accretion is actually surprisingly high in the South European countries at certain regions. In principle the degree of icing and number of icing days decreases from south to north, and within individual countries also increases with the site altitude. However, taking into account the latitude and altitude it could be observed that the icing is more severe problem e.g. in the Apennines and Mountains in the South France than in coastal and low land areas in Northern Scandinavia.

5.2 Aerodynamics and Loads

In order to estimate the changes of loads and power production due to icing, the effect of different types of ice accretion on wind turbine blades has to be known. The necessary information was gained by experiments, measurements and simulations described in various WECO publications.

Partly empirical equations and methodologies have been developed, verified and published. The strategy for estimating the effect on loads and power production for wind turbines with iced blades by using the WECO data is depicted in the following scheme:

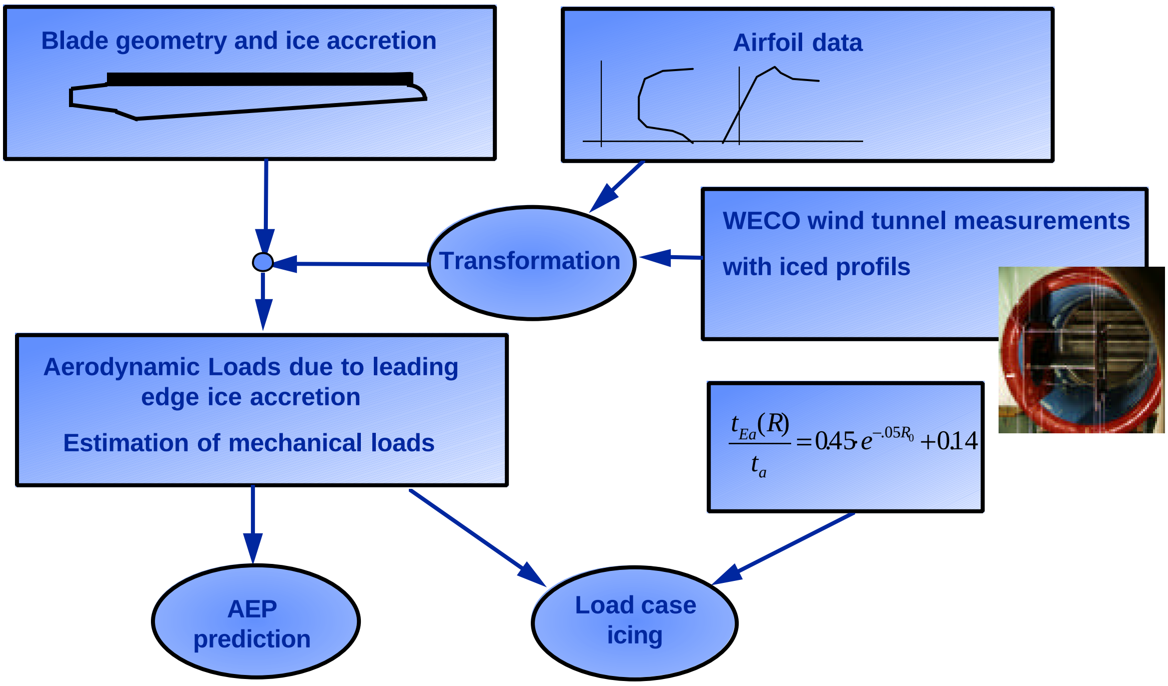


Figure 7. Principle flow chart for load and energy production calculation of wind turbines with iced rotor blades

5.2.1 Icing of the blade

During the rotation of the rotor blades in icing weather conditions the leading edge of the rotor blade collects more and more ice around the stagnation points of the airfoils over the radius. Due to the increasing air velocity along the radius, the ice accretion builds up more at the outer part of the blade with an approximately linear increase [1], [2] which is depicted in Figure 8. With growing ice accretion the drag of the airfoil increases diminishing the power output of the turbine. It was expected that the chord length should also increase the lift at the iced cross section of the blade and thus, increase the bending moments at the blade root [19]. However, the ice at the leading edge obviously also diminishes the lift coefficient at a given angle of attack which compensates the effect expected. Due to the growth of chord length at the leading edge the pitching moment increases dramatically which is very important for instance for the pitch control mechanism.

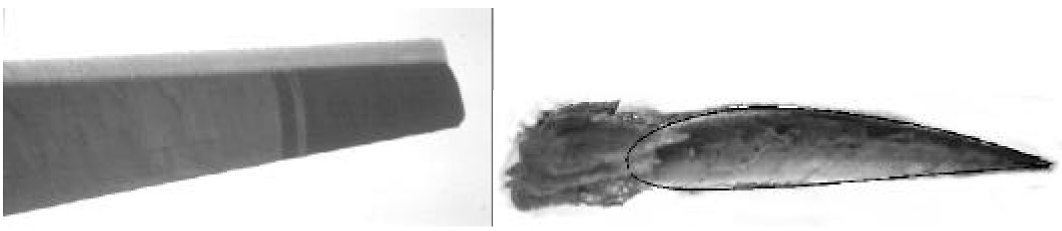


Figure 8. Typical leading edge ice accretion monitored during the WECO project.

In order to enable wind turbine designers to predict loads and energy losses for wind turbines operating under icing conditions it is necessary to qualitatively and quantitatively know the changes in the aerodynamic properties brought about by ice accretion on the blade’s leading edges. Within the **WECO** - project this problem was investigated for rotor blades in different stages of icing by:

- observations (videos, questionnaires, photos, collection of ice fragments)
- wind tunnel tests in low temperature wind tunnel simulating icing conditions [10]
- simulation by predicting the ice accretion using computer codes and models.

The assessment of ice accretion on rotor blade's leading edges is also an important input for computational ice models. These computer codes model the mechanisms of ice built up during operation and are valuable tools for the design of heating and anti-icing systems [5], [10].

Wind tunnel tests have been carried out using "artificial" iced profiles with various types and amount of ice accretion. This information was used as input for computer models for load and power output prediction of iced rotor blades. Various wind tunnel tests at the Technical University of Braunschweig were carried out in order to investigate typically iced airfoils.

Most of the observations of iced rotor blades during operation showed that the ice built-up is linear from the blade root to the tip with a maximum depth of ice accretion at the outer part (see also Figure 1). The ice at the outer part of the blade breaks off and grows again during operation forming a saw-tooth-distribution described e.g. by Seifert in [20].

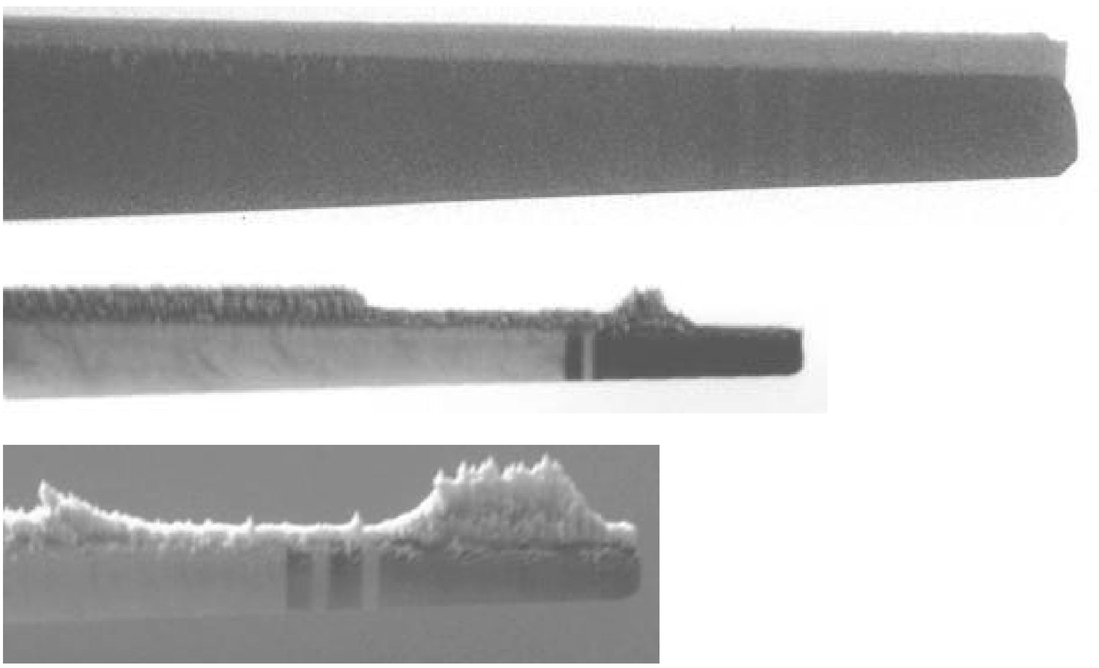


Figure 9. Icing under different modes of operation. Top: Beginning of icing during operation; middle: re-icing after ice throw during operation; bottom: icing during idling.

The effect of simulated ice accretion on the aerodynamic performance of a modified airfoil was studied experimentally. Leading edge ice accretion was investigated in the wind tunnel for a range of values of the ratio of ice length to chord (2.5 % up to 44 %). The ice fragments have been collected from observed wind turbines operating in icing conditions. Stationary and instationary 2-dimensional data of lift, drag, and aerodynamical moment coefficients have been extracted in an open jet wind tunnel for angles of attack in the range of -10 degrees to 30 degrees. Also the TURBICE-model was used to study the ice shapes (as shown in Figure 10), maximum ice loads and the location of the heating elements on a blade [5].

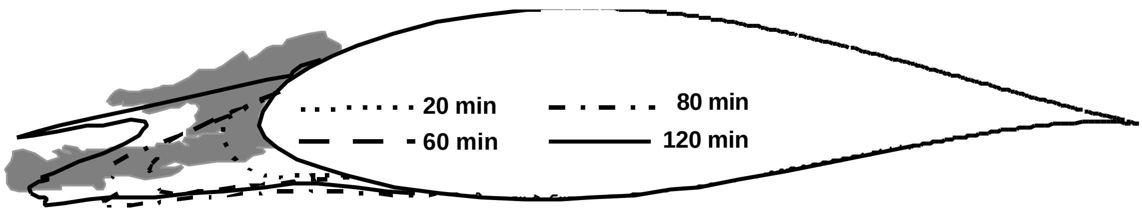


Figure 10. Simulated ice accretion as the function of time (min) for a 600 kW stall regulated machine at tip (radius 18.5 m) and the comparison against an experimentally gained ice accretion found at a turbine of similar size.

A simplified ice mass distribution along the rotor radius which has been adopted following the recommendations of the German institute for building techniques DIBt [20] and the Germanischer Lloyd [6] was verified by the measurements and observations of the investigations on iced profiles during the WECO project.

5.2.2 Aerodynamics

Collection of Ice Fragments

The shapes of ice on the leading edge to be investigated in the wind tunnel were taken from plaster models moulded from ice pieces found close to iced wind turbines.

In order to preserve the ice it was put into a bucket containing model-plaster. After hardening and melting of the ice a negative mould remained. This has been casted out with epoxy resin and filling material using a special technique. The resulting resin model was used as the basis for the wind tunnel measurements described. Derived from this masterpiece, a silicon resin negative mould was manufactured in order to multiply the cross section of the "artificial" ice. The masterpiece and the final ice accretion model for the wind tunnel test are exemplary shown in Figure 11.

Simultaneously, a NACA-4415 profile that represents the outer cross section of the rotor blade where the ice accretion was gained from was manufactured with the original chord length and profile shape [20].

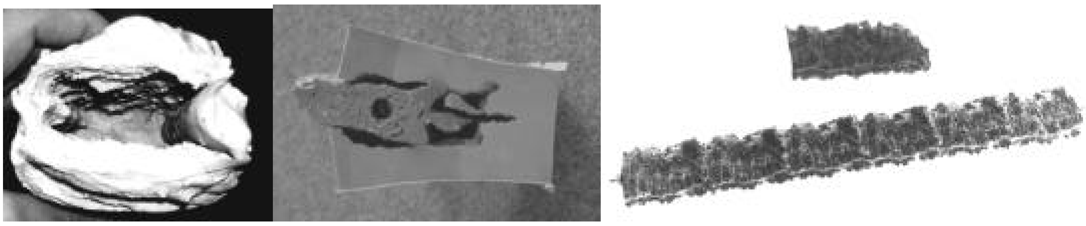


Figure 11. Plaster mould, silicon negative mould, masterpiece of the leading edge ice accretion and its duplicates for the wind tunnel model (left to right).

The artificial ice at the leading edge represents an ice built-up of more than 20 per cent of the chord length. The leading edge ice cross section is typical for this type of rough ice (Type B in Figure 12). The different types of leading edge ice accretion were defined according to the specific influence on drag and lift versus angle of attack behaviour within the measurements.

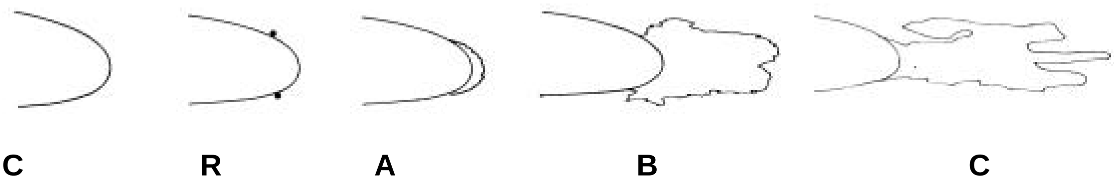


Figure 12. Typical catalogued leading edge ice cross sections. Clean Rough Type A Type B Type C

Fourteen ice fragments have been catalogued and half of them have been tested in the wind tunnel. For some of the fragments, which are stored in a database, the meteorological conditions during the icing event are also partly known.

For the verification of ice models an ice accretion at the circular cross section of a radial guy rod at the rotor blade of the small wind turbine was collected. The ice amount versus rotor radius of this rod follows the linear function observed for leading edge ice accretion of the rotor [1].

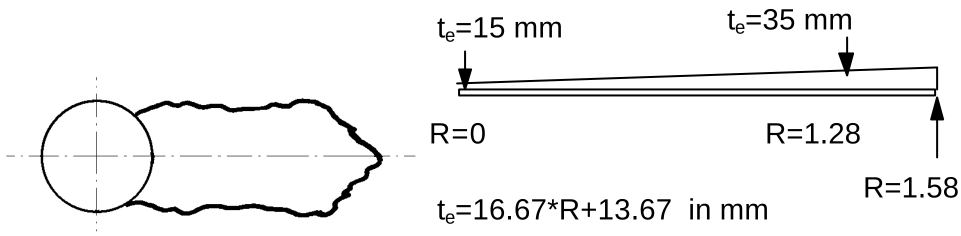


Figure 13. Pitch control rod ice accretion (as measured at the INVENTUS turbine at DEWI's test station)

Wind Tunnel Tests

The influences of different ice shapes and sizes were investigated in the wind tunnel of the University of Braunschweig. Coefficients of lift, drag and aerodynamical moment were measured at the original clean airfoil and with added leading edge ice models at a Reynold's number of 630 000 using direct force measurements in an angle of attack range between -10° to 30° degrees. All coefficients described are defined by the original chord length of the non-iced airfoil, in spite of the larger chord length (larger area) with ice accretion. As a basis airfoil for the measurements, a NACA4415 was chosen [21]. The blades which have been investigated concerning icing earlier [19], [1] as well as those on a small turbine at the DEWI test station [20] use the same type of airfoil. Using the original cross section from the blade close to the tip a rectangular wind tunnel model was manufactured with a chord length of 225 mm and a wing span of 500 mm. The ice accretion was modelled by duplicating the fragments found at the original turbines.

Figure 14 on the left side shows the position of the model without ice accretion between the end plates fixed by wires in the centre of the open measurement cross section of the wind tunnel with a diameter of 1.3 m. Six load cells measure the forces which are further amplified, stored and evaluated by a data acquisition system.

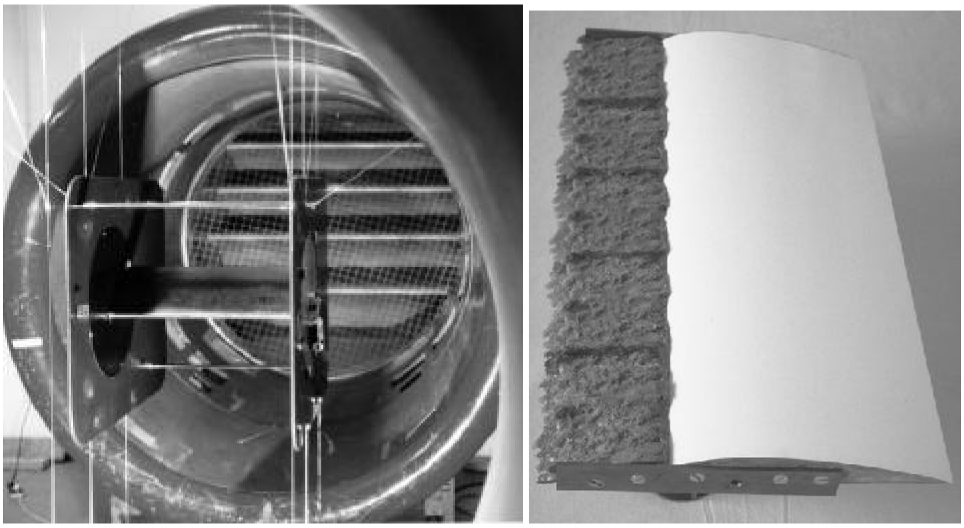


Figure 14. Open measurement cross section of the wind tunnel at University Braunschweig and wind tunnel model used in earlier measurements.

The influence of the wires and the end plates of the wind tunnel model on the measurement were calibrated in a first measurement campaign.

Stationary measurements

The airfoil characteristics of the clean and different iced sections are summarised in Figure 15 for the lift coefficients versus drag coefficients and lift and aerodynamical moment coefficients versus angles of attack. There is a remarkable difference between the ice accretion type B, with 22 per cent and the type C, with 44 per cent ice accretion respectively. The reason can be seen in the shape of the ice accretion especially the sharp edged plate of the 44 per cent type. The maximum lift coefficient of this type is higher and the minimum drag coefficient lower, respectively, compared against the 22 per cent ice accretion.

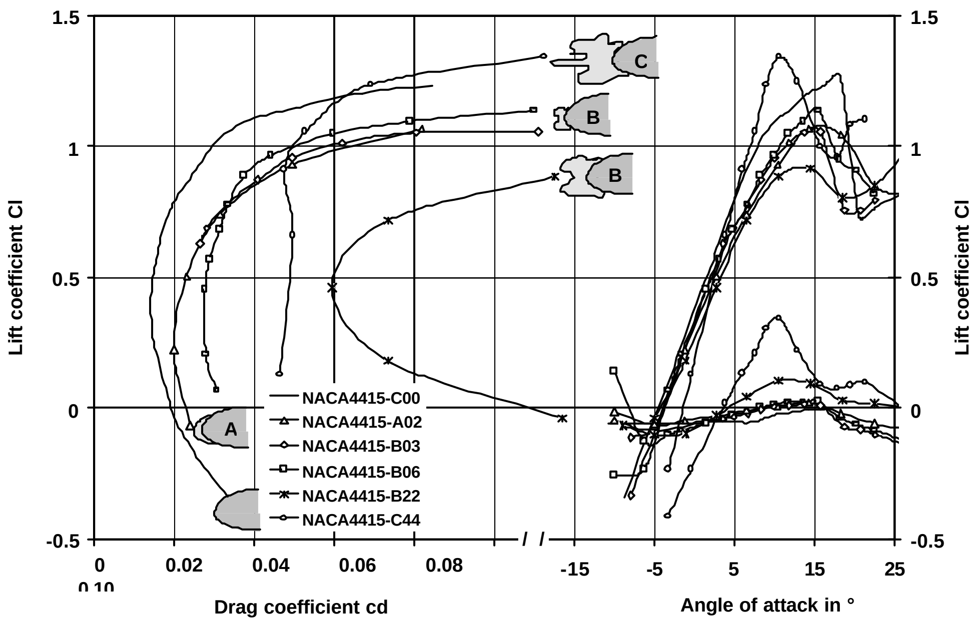


Figure 15 Typical result of wind tunnel measurements: Lift coefficients c_l versus drag coefficient c_d for the various ice accretion models A, B and C (left side) and lift and aerodynamical moment coefficients c_m versus angle of attack a (right side).

Instationary measurements

Also instationary measurements were performed for the iced and non-iced cross sections in order to investigate the influence of icing on the dynamic stall behaviour. Figure 16 represents a typical measurement of the clean and the iced profile with 22 per cent leading edge ice accretion. As can be seen there is no significant change of the behaviour if iced and non-iced $c_l(\alpha)$-curves are compared. However, a shift of zero-lift angle of attack of the iced airfoil can be seen compared to the clean one as well as a lower amplitude of the maximum and minimum lift coefficient in the stall region for the iced section. Thus, influences on the dynamic behaviour in the post stall region can expected.

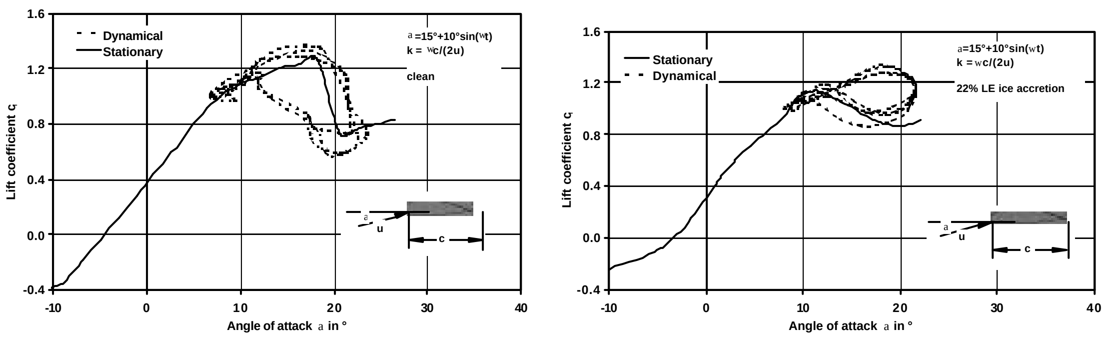


Figure 16. Stationary and instationary measurements with the clean airfoil (left side) and instationary measurements with the iced airfoil (22% type B leading edge ice accretion, right side of the Figure).

Due to the suspension of the wind tunnel model the variation of the angle of attack versus time was limited to k-values of K = .022. The angle of attack amplitudes are described with equation (1) whereas the k-value is explained in equation (2) with c being the chord length of the airfoil and u being the speed of the air inflow.

$$a(t) = 15° + 10° \sin(wt) \tag{1}$$

$$k = \frac{wc}{2u} \approx 1Hz \tag{2}$$

Transformation of wind tunnel results to other airfoils

A method for transforming the measured aerodynamic coefficients from the iced NACA4415 airfoils to any other airfoils below:

First, the angle of attack ranges have to be defined at both of the airfoils, the new airfoil (index NP) for which the coefficients with ice accretion are searched and the well known iced and uniced NACA4415 (index NACA). Also the stall behaviour of the particular airfoil has to be known and influences the transformation and the extrapolation, respectively.

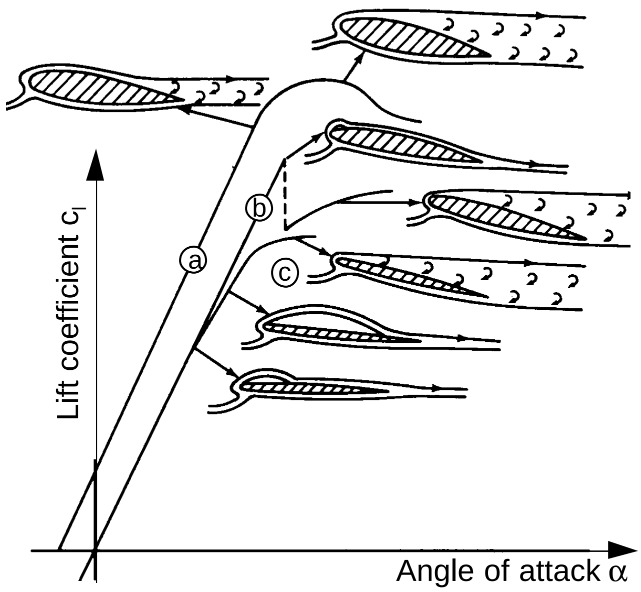


Figure 17. Different types of stall and the resulting $c_l(a)$ curves

Three basic types of stall are recognised: First, the trailing-edge stall that occurs when the flow begins to separate at the trailing edge, and with increasing angle-of-attack, the separation gradually progresses towards the leading edge (line a in Figure 17). This is considered as a gentle type of stall and more desirable than other types, since the lift decreases gradually from its maximum value. Secondly, the leading-edge stall which starts as a short bubble formed in the vicinity of the leading edge (line b in Figure 17). When it bursts, a rapid change of flow over the upper surface of the airfoil occurs, resulting in both a sudden drop in lift and an increase in the profile drag. Thirdly, the thin-airfoil stall, which starts with a long "stable" bubble which elongates gradually and eventually bursts (line c in Figure 17). The type of stall is strongly influenced by the geometry of the front part of the airfoil section within 10 to 15 percent from the leading edge; the most important factors being the shape of the mean-line curve between 0 and 15 percent of chord length, and the leading-edge radius. The user of the transformation has to decide, which type of stall occurs for his particular airfoil. In case of a trailing-edge stall, the Viterna's equation [24] will be used from the stall angle which must be declared before in the program. In case of leading edge stall, which has been the case for the measured NACA 4415 profile, the Viterna's equation will be used from an angle of attack of 25 degrees.

Basis for the transformation are the zero lift angles of attack a_o and the angles of attack $a_{cl,max}$ at the maximum lift coefficient $c_{l,max,}$ respectively:

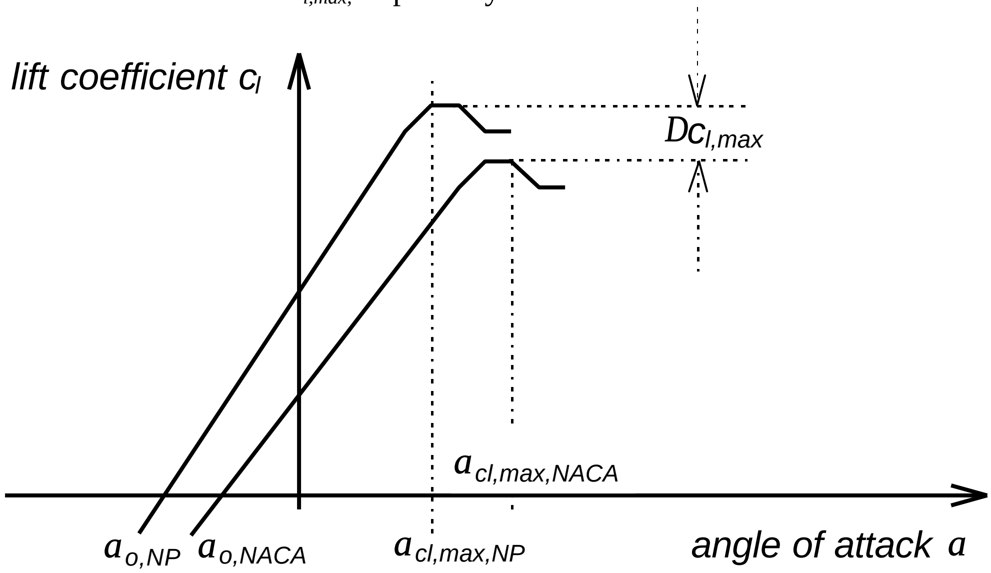


Figure 18. Method to interpolate the "iced" coefficients of the airfoils:

$$a_{NACA} = a \cdot a_{NP} + b \qquad \text{with}$$

$$a = \frac{(a_{cl,max} - a_o)_{NACA}}{(a_{cl,max} - a_o)_{NP}} \qquad \text{and} \qquad b = a_{o\_NACA} - a^* a_{o\_NP} \tag{3}$$

The transformation of the angle of attack of the new airfoil for which the Dc_l, Dc_d and Dc_m values are searched at the angle of attack of the clean NACA4415 profile (see Figure 18). The interpolation of Dc_l, Dc_d and Dc_m of the NACA4415 - coefficients for the chosen ice accretion follows. Further the multiplication of the differences with the factor gained from the difference between the maximum lift coefficient of the new airfoil and the NACA4415 airfoil as given in equation (4) has to be carried out:

$$K_a = \frac{c_{l,max,NP}}{c_{l,max,NACA}} \tag{4}$$

Finally, the differences are added to or subtracted from the related coefficients of the new airfoil. Figure 19 shows the result of the transformation method described above for a NACA 63-415 airfoil.

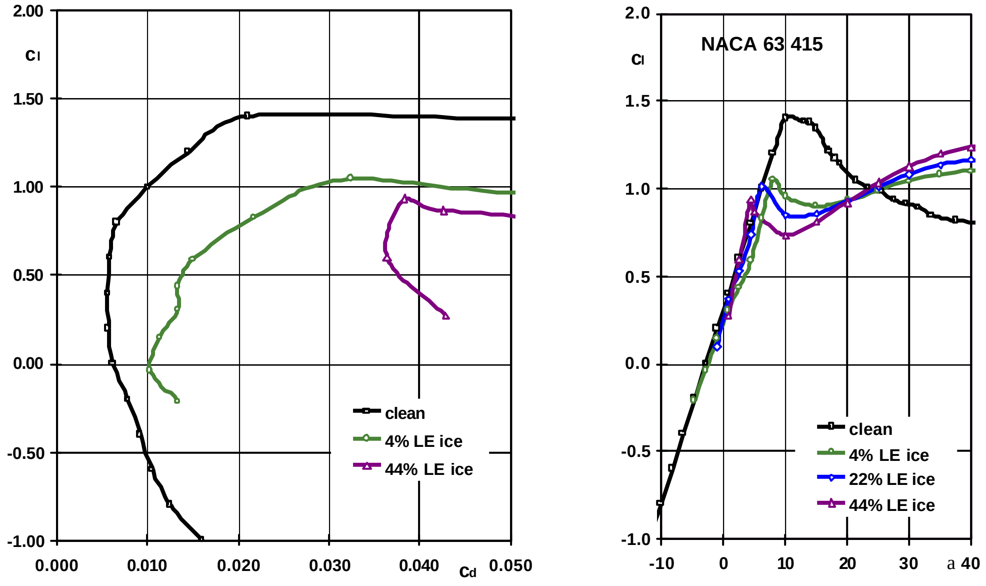


Figure 19. Example for the aerodynamic coefficients of an "iced" NACA 63-415, determined by the method described.

Extrapolation to post stall Region

Most of the aerodynamic codes for calculating loads and power output require high angle of attack values. Depending on the type of the wind tunnel and the method of measuring, the aerodynamic coefficients for angles of attack up to a maximum of 30° could be assessed. However, the behaviour of an iced airfoil and a flat plate at high angles of attack are comparable. The method described in the following uses Viterna's approach for the interpolation between the measured curves and the flat plate values, respectively [23].

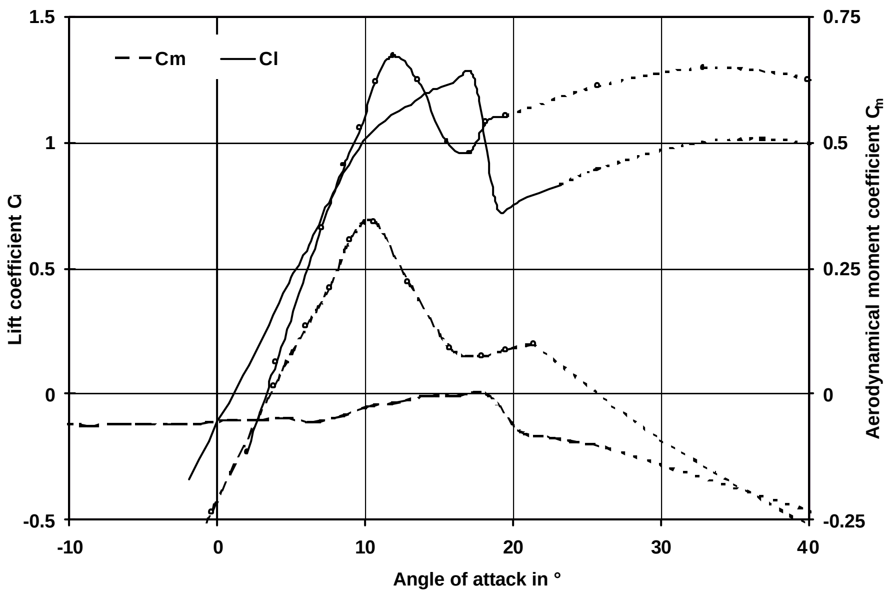


Figure 20. Extrapolated lift and aerodynamical moment coefficients versus angle of attack.

Figure 20 shows measured and extrapolated values of c_l and c_m for angles of attack up to 40°. The measured and interpolated flat plate data are marked differently.

The coefficient of the aerodynamic moment at zero lift c_{m0} is derived from measurements or has to be defined. Figure 21 shows the definition of the sign of the aerodynamic moments and the simulation of the "iced" flat plate for high angles of attack.

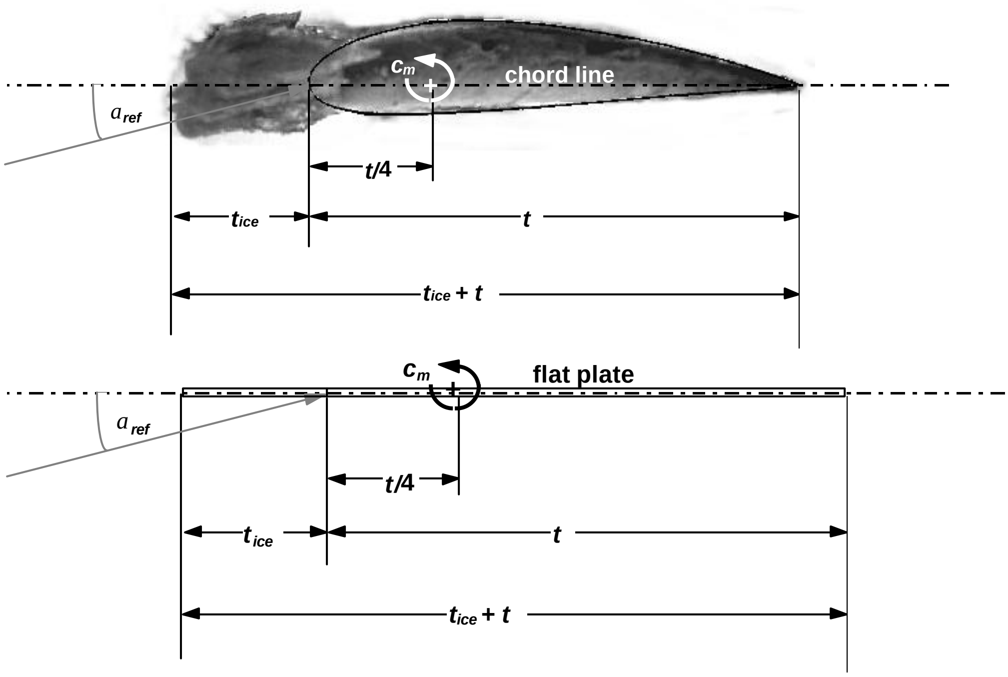


Figure 21. Original iced profile and model of flat plate with "ice" extension.

5.2.3 Loads

Certifying wind turbines for cold and mountainous regions requires reliable procedures for the prediction of ice amount during standstill and operation. International design standards take icing load cases into consideration in different ways. The IEC-61400-1 ed2 Wind Turbine Generator Systems - Part 1 Safety Requirements recommends to take ice loads into account but a special load case is not given. However, investigations concerning icing of wind turbines during operation at different places in Europe showed, that heavy ice loads are not negligible. Thus, based on these experiences a proposal for simplified load assumptions for design codes has been worked out in [1]. However, the distribution forming the highest ice mass is the linear distribution. A method taking this distribution into account for load calculations described below. The maximum depth of ice amount at the tip is thereby dependent on the blade's chord length. Measurements and observations for different sized wind turbines are known and were used as a basis for the approximations.

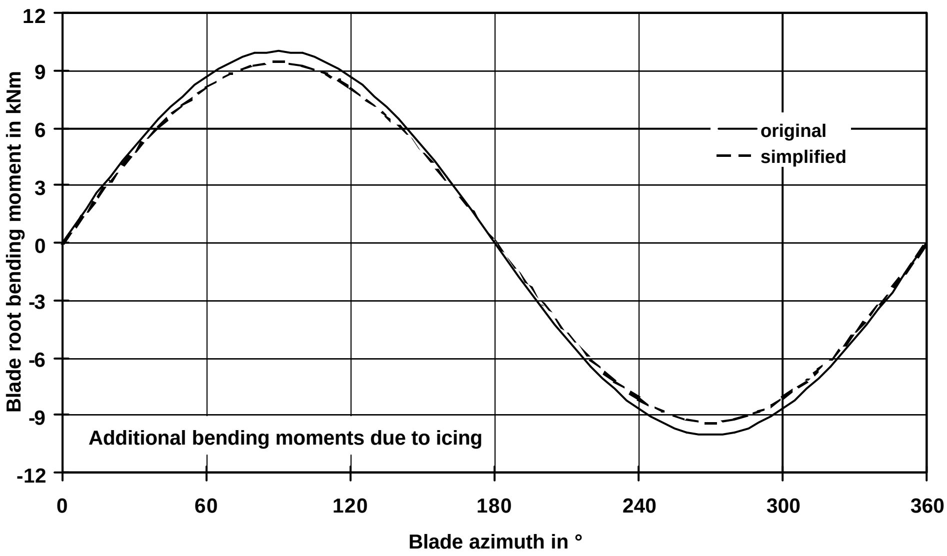


Figure 22. Additional edgewise blade root bending moment for a fictitious 300 kW turbine

In Figure 22 the additional blade root bending moments in edgewise direction are shown for a fictitious 300 kW turbine calculated with the simplified and the more realistic [24] prediction method for the leading edge ice accretion. This method describes how to take the additional masses into account. The changed aerodynamic loads have been calculated using the aerodynamic coefficients of the wind tunnel tests described. The blade loads in the flapwise direction are depicted for a pitch controlled turbine. In the partial power region the loads are decreased due to icing whereas beyond rated wind speed higher loads, even the highest loads can occur.

According to the models and experimental data it was found that icing reduces the standard deviation of the flapwise bending moment, increases the standard deviation of the bending moment in edgewise direction slightly and increases the fluctuations of the tower root bending moment a lot. The power spectral density of the flapwise bending moment is found to be reduced at 1P and not to change significantly at any other frequencies. The power spectral density of the edgewise bending moment is found to be increased by a factor of five at its natural frequency - indicating increased risk of edgewise vibrations. The power spectral density of the tower base bending moment is increased at 1P and at the first tower natural frequency. The few existing data measured at Pyhätunturi test site in northern Finland at high wind speeds were investigated for edgewise vibrations *[26*]. As expected, strong stall induced edgewise vibrations were found. Unfortunately, the exact amount and shape of icing remains unknown for all the recorded high wind speed measurements at Pyhätunturi. Concluding it can be said that dangerous ice induced tower vibrations were found at wind speeds below stall, and that extreme stall induced edgewise blade vibrations were found at around 25m/s during possible icing conditions.

Results from the measurements performed during the WECO project is that operation under heavy icing is not recommended, so in these situations shut down of the turbine or using a blade heating system is recommended. As the influence of operation under the different icing conditions on the lifetime of the turbine's components are not predictable in general terms possible effects of icing on the fatigue loads are tabled below. The experiences drawn from the observations and different measurements are included in this table which is aimed at the designers of wind turbines and certification bodies.

Icing is increasing fatigue loads	**Icing is decreasing fatigue loads**
additional ice masses cause higher deterministic loads	icing might increase the aerodynamic damping and thus diminishes in some cases the vibration of components
asymmetric masses cause unbalance	shut down of the turbines due to frozen anemometer/rotor and the consequential stand still for longer periods reduces the number of load cycles
increased excitation of edgewise vibrations has been observed due to icing as well as higher tower vibrations.	operating at lower rotor speeds (two speed generators or variable speed operation) due to iced blades lead to lower load cycles but eventually higher amplitudes due to higher deterministic loads
Ice accretion affects the control system. Resulting vibrations have been observed during the WECO project.	
Yaw error due to frozen wind vane of the control system may lead to higher load amplitudes.	
Pitch turbines operating under stall conditions due to changed aerodynamics.	
Resonance may occur due to changed natural frequencies of components such as rotor blades. Especially for smaller turbines and light weight rotor blades.	

5.3 Safety

Ice throw from the rotating blades is an important problem when the site of the wind energy power plant is planned to be close to public roads, housing, power lines etc. Ice throw has been studied using both theoretical models (Garrad Hassan) and experimental data (the questionnaire etc.) from various WT sites. This work has progressed as far as possible with the data available. The preliminary results were reported in Gothenburg 1996. The results are given in the form the number of ice fragments likely to fall within a 1 m^2 patch in the vicinity of a wind turbines (N_{point}) in any one year as a distance from the wind turbine.

According to the data and models developed and verified within the project it can be recommended for sites with high probability of icing to keep a distance d_{ice} between the turbines and nearest objects of about

- d_{ice} = 1.5·(hub height + diameter),
- or it can be recommended to stop the turbine automatically during the icing period and wind coming from unfavourable directions, if the public safety might be affected by ice throw.

The results of the ice throw calculations are given in the form the number of ice fragments likely to fall within a 1 m^2 patch in the vicinity of a wind turbines in one year at a certain distance from the wind turbine [10].

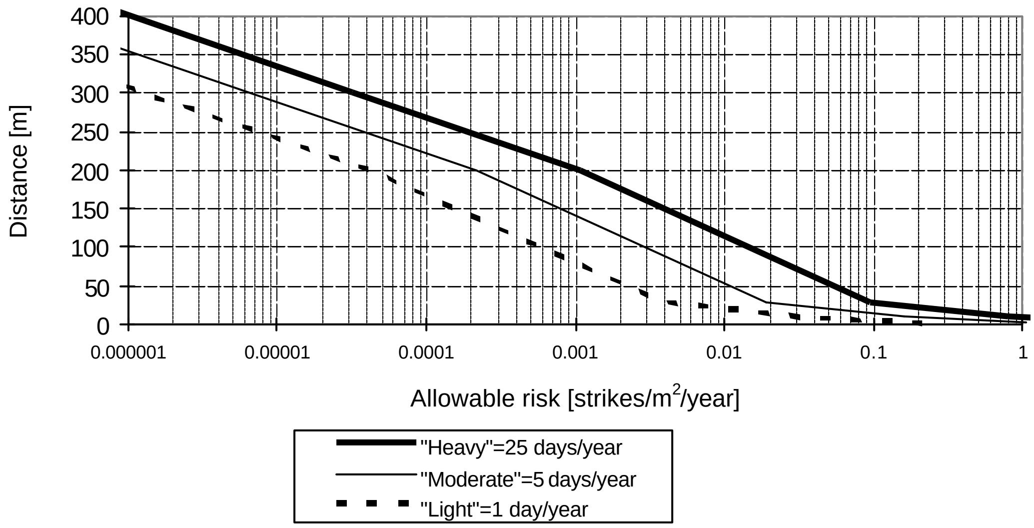


Figure 23. Safety distance for different icing levels (50m rotor) [7].

In a situation where a significant risk to the public or operational staff due to ice throw is believed to exist, the following measures are suggested:

i. Curtailing operation of turbines during periods of ice accretion.

ii. Implementing special turbine features which prevent ice accretion or operation during periods of ice accretion.

iii. Re-siting of the turbines to remove them from areas of risk.

iv. The use of warning signs alerting anyone in the area of risk.

v. Operational staff should be aware of the conditions likely to lead to ice accretion on the turbine, of the risk of ice falling from the rotor and of the areas of risk.

Existing building regulation deal very poorly with the icing problem, and of course ice throw from wind turbines is a new issue. For instance in Finland this given formula for d_{ice} is now used for some new WT sites close to skiing resorts. In Germany the insurance companies have a great interest in the possibility of ice throw, especially when the turbine is planned to be close to public roads.

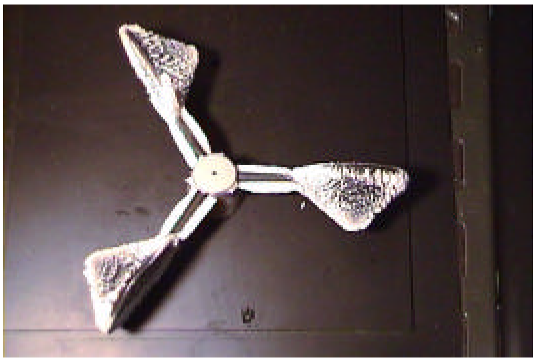
Safety, and also productivity, of a wind turbine operating under icing conditions can significantly be improved also by using blade heating system [34], to avoid ice accretion on blades.

5.4 Anemometers

Anemometers are a small but essential component for wind power assessment and operation of wind turbines. It is also the most easily corrected part of the icing problem, if correctly identified and taken into account.

Even a very small amount of ice on unheated, non-ice-free anemometers will effect the wind measurements significantly [8], [25]. Often slight icing of the anemometer can not be observed from the ground (Figure 24 a), or in the data analysed and used afterwards, when the anemometer has been rotating with reduced speed. Anemometers can also be totally sized with ice (Figure 24 b).

Icing of anemometers will affect assessment of the wind energy potential (under prediction of wind speed) and the operation of WTs (wrong control data).



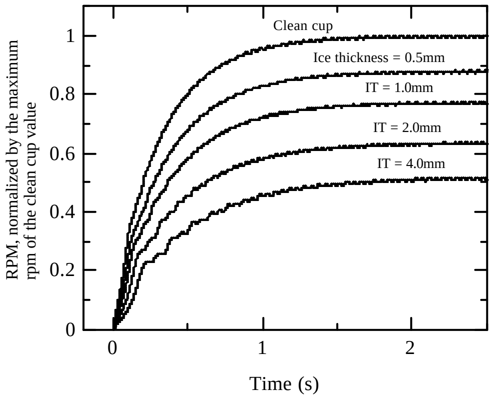


Figure 24. a) An example of rime accretion upon a WAA unheated anemometer in wind tunnel tests. In this case the wind speed was reduced by 30 %. b) Results from a theoretical study on reduction of measured wind speed as a function of operation time (s) of the anemometer and thickness of rime (mm) on the cups. In this case e.g. 1mm rime on cups reduces the measured wind speed by 22 %, and 4 mm 50 %. [12]).

At most of the meteorological stations affected by icing conditions the annual and monthly wind speed is underestimated due to use of non heated anemometers. The degree of the underestimation varies strongly from region to region in Europe [3], [8].

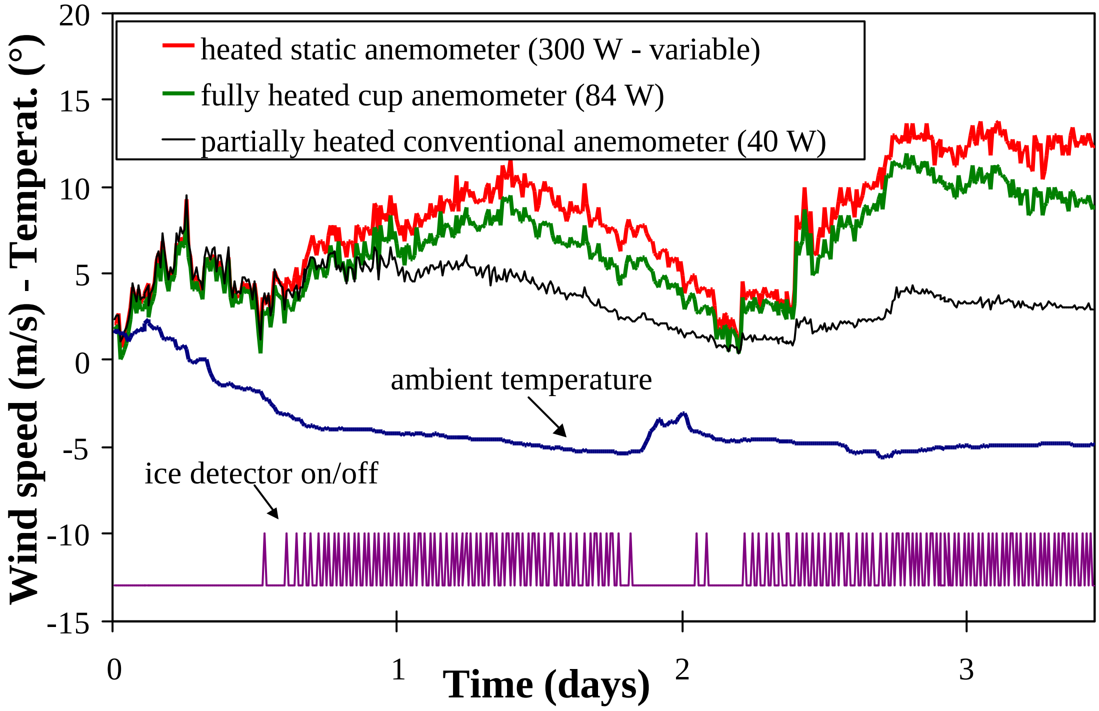


Figure 25. Icing of anemometers observed at ENEL wind power station in Acqua Spruzza, Italy (1350 m a.s.l.). The period of icing is observed by the Rosemount ice detector (below). The reduction of wind speed in this case goes up to some 80 %.

Ice free wind gauges, such as anemometers and wind vanes, have absolutely to be used at sites where icing conditions may occur frequently during the cold season. It is obvious that at heavy icing conditions which occur in the Alps, Apennines and other high mountain areas, and at Scandinavian and arctic hills the operation of WTs during the winter months is impossible due to iced anemometers and iced blades. According to the information from UK, it is obvious that the greatest problems due to icing are caused by iced wind gauges.

At present only few ice-free wind gauges are available on the market. Some of them are suitable only for conditions with minor icing (coastal areas in Northern Europe). Only one or two gauges tested by the WECO project can survive even the most harsh icing conditions, but some of them are too sensible for slope winds (Figure 26) indicating too high wind speeds at these conditions [8], [11], [15]. By the experimental data and wind tunnel analyses it was also observed, that some of the heated gauges are very sensitive to tilt effect, which is typical especially at mountainous sites, leading to a measurement error of wind speed up to some 10-12 % (Figure 26). Thus, there is a need for improved wind gauges designed for heavy icing conditions.

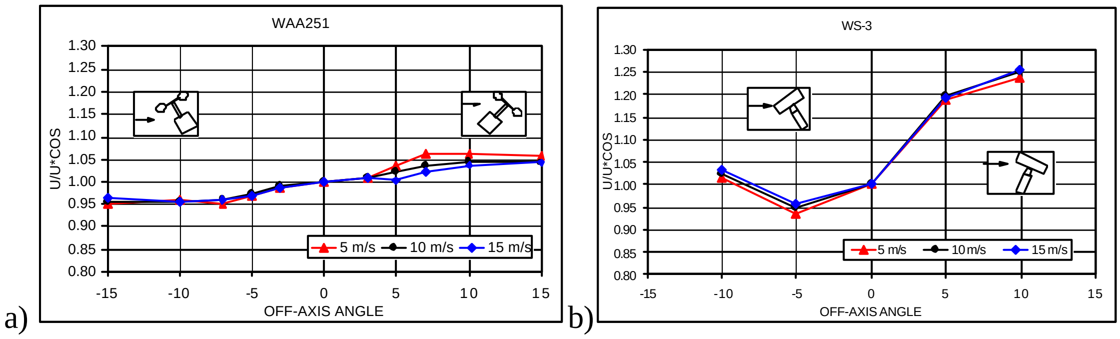


*Figure 26. The effect of off-axis angle on measured wind speed presented as the ratio R_q = (V_m/V_0)*cosq (V_m is measured wind speed, V_0 undisturbed background wind speed, and q the tilt angle) for three different wind speeds. a) WAA251 and b) Hydro-Tech WS-3 [3].*

The markets for ice-free anemometers are very large, and not only in Europe, due to the new wind power plants.

5.5 Ice detectors

Ice detecting systems are needed to give information of icing conditions to identify real time icing of blades during unattended operation. It is also important to know if the blades are still iced, to be able to re-start the turbine without any danger to the public after the icing period. Ice detecting system can also be used to control the heating system of blades.

Within the WECO project two ice detecting systems have been discussed and studied:
- ice detectors
- multi - anemometry (one heated, one unheated).

The Finnish Labko ice detectors were used and tested at various WECO test sites.

The experimental data from the test sites proved that ice detecting system is usable at icing sites.

At present there are not too many suitable ice detectors available, as shown by the market survey [15].

5.6 Power production

The effect of icing upon power production is studied by models and by field measurements in order to improve the methods to estimate the monthly and annual loss of energy production of wind turbines operating under cold climate conditions.

5.6.1 Power measurements

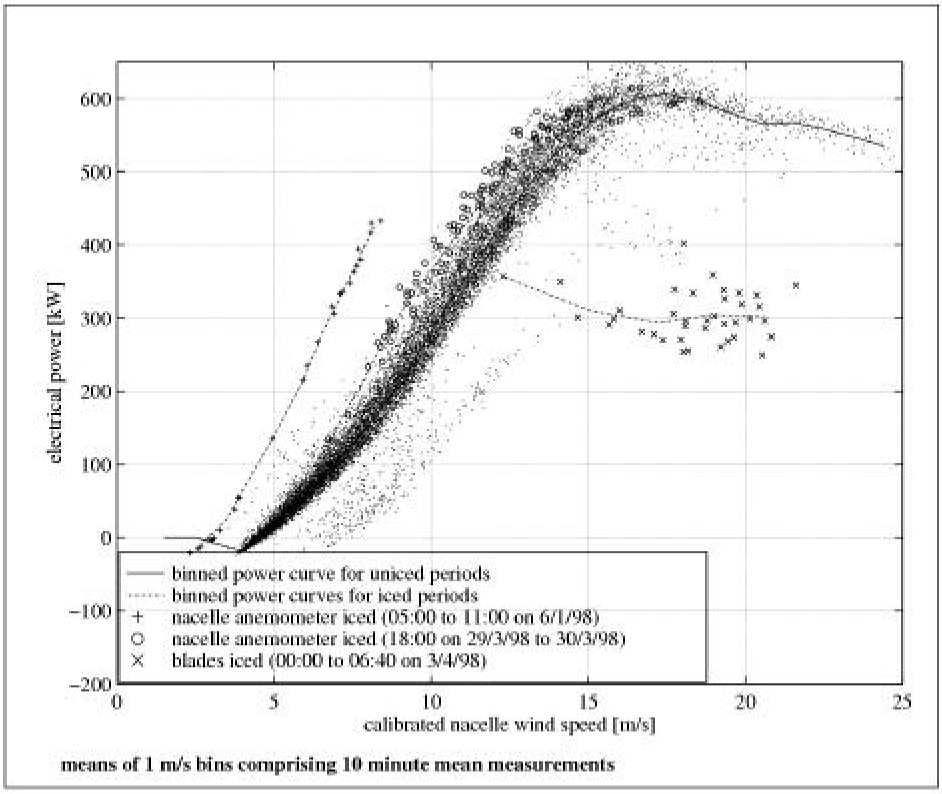
<u>Windy Standard</u>
The power curve measurements for the NEG-Micon (Nordtank) 600/37 wind turbine at

Windy Standard included substantial periods when icing conditions were prevalent as well as long periods through the summer of 1997 when it was known that no icing was occurring.

Measured power curves for the wind turbine are shown in Figure 27. The solid line shows means of 1 m/s wind speed bins for periods when the following conditions were satisfied:

- the turbine was at synchronous speed and not wake-affected
- neither the turbine nor sensors were subject to icing

It should be noted that the wind speed on this plot is measured on the nacelle, without further adjustment and is therefore approximate.



Power and wind speed without the effects of other turbine wakes (with standard turbine power curve for reference).

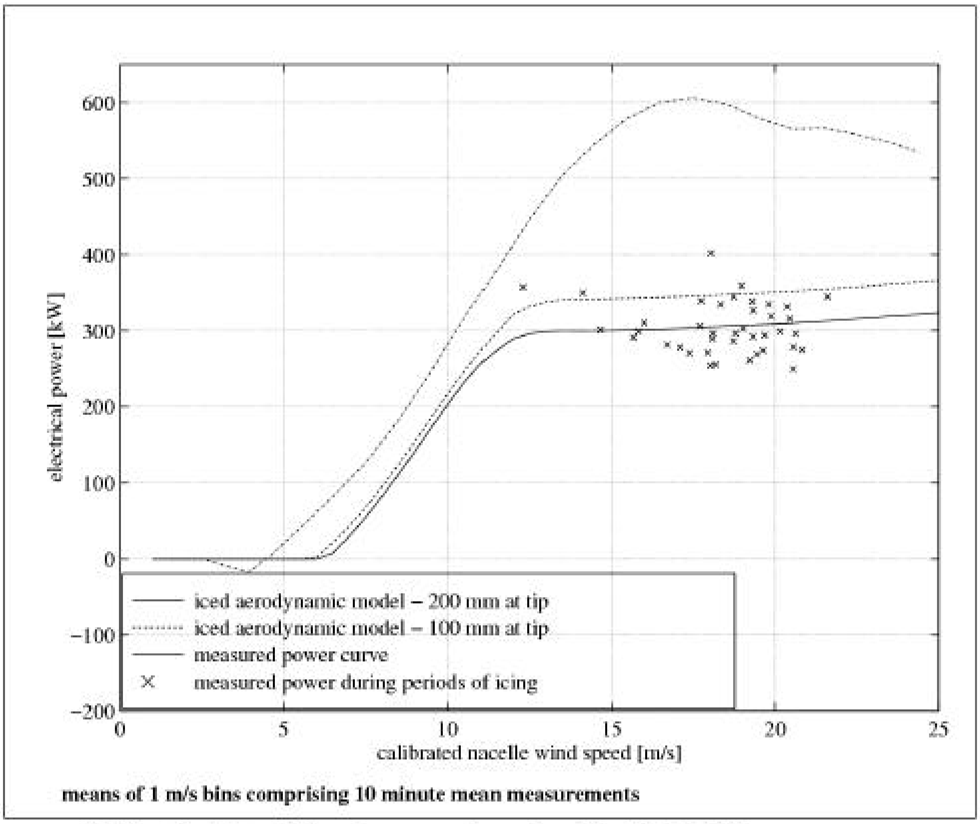
Figure 27. NEG/MICON 600/37 at Windy Standard.

5.6.2 Theoretical modelling

The effect of blades icing on the power curve was studied using codes like BLADED, PROPcode and modified PROPcode.

<u>BLADED</u>:

For many of the periods when icing occurred at Windy Standard, the ice build-up on the P11 turbine was observed on video. Combined with the C_l and C_d coefficients described in Figure 15, this allowed a range of power curve predictions to be undertaken using the Bladed for Windows model of the turbine. These predictions are compared to the measured data in Figure 28. This figure shows the predictions for the condition of no icing, light icing and moderate icing.



Modeling the effects of icing using an aerodynamic model of the iced blade for which the thickness of ice measured outwards from the leading edge of the blade reduces from the blade tip to zero at the blade root.

Figure 28. Windy Standard power curve predictions and measurements with the effect of icing demonstrated.

<u>The PROP code:</u>
The C_l, C_d values produced in the WECO wind tunnels tests (see Figure 15) are used for the PROP code to calculate the expected power output during various types of icing conditions], [28], [18]. The power curves can be used to predict the wind power production at chosen site when the wind speed and icing conditions are known.

The PROP-code computer program, was developed by R.E. Wilson (Oregon State University), P.B.S. Lissamen (Aero Vironment Inc.), established by S.N. Walker [29] and improved by B. Hibbis and R.L Radkey [30]. During the WECO project the code was modified by prof. S. Kimura.

The calculations of the PROP-menu 2.1 are based on the blade element theory. Hereby, the rotor blade will be cut into ten equal elements with the chord length Δr shown in Figure 29. This determination is received by input of the twist, the chord length of the blade, the profile type and the lift and drag coefficient. Moreover, it is possible to specify the wind turbine by indication of the hub height, the rotor diameter, the number of revolutions and the cone angle. For the calculation of the icing effect it is expected that ice is formed on the leading edge

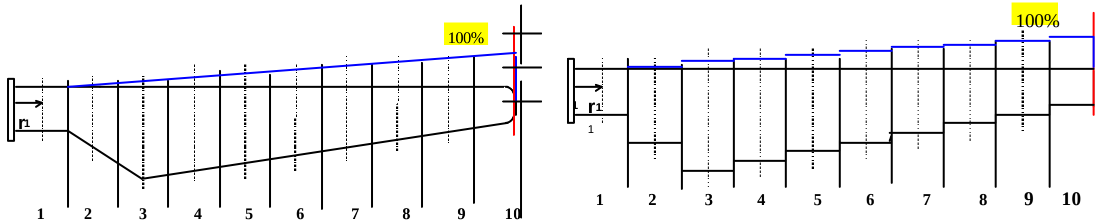


Figure 29. Original rotor blade (left) and the PROP-code rotor blade with assumed ice shape on the leading edge. The amount of ice is given as a proportion of ice l_{10} to the chord length of the blade at the tip L_{10} [28].

The amount and shape of the ice on the leading edge was as used for the wind tunnel experiments of C_l and C_d (as shown earlier). The power curves under icing conditions (type A, B, C and D) were calculated for a standard stall and pitch regulated 500 kW turbines. Some of the results are given in Figure 30 a-b.

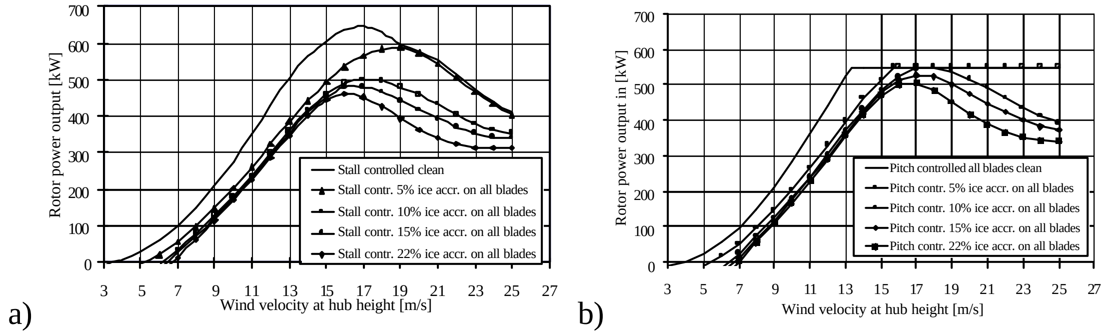


Figure 30 a-b. Rotor power curves for a 500 kW stall (a) and pitch (b) controlled wind turbines under clean and iced conditions. The amount of ice is given for tip section of the blade.

The pitch controlled turbine shows better results in all cases for a wind speed range from 15 m/s up to the cut-out wind speed at hub heights. Still the results show, that energy loss increases strongly with increasing amount of ice accretion on all three blades.

5.6.3 Icing effect on power production in various parts of Europe

The icing effect on power production of the desired site can be predicted knowing the average annual wind speed distribution (typical WA^{S}P analyses), the wind distribution during different amounts of leading edge icing, icing effect on the power curve and needed stand stills due to icing for e.g. safety reasons. The icing effect on annual power production is larger at sites where the wind speed is much higher during the winter than in summer. Some results are shown in Figure 32 a-d.

Two methods to study icing effect on power production were chosen:

- experimental, based on continuous data from WT test sites and on replies to the questionnaires
- calculation, where the produced C_l and C_d values are used to calculate the power curves for certain types and amount of ice, and the on-site duration of wind distribution for each type (A, B, C) of icing is taken from meteorological observations.

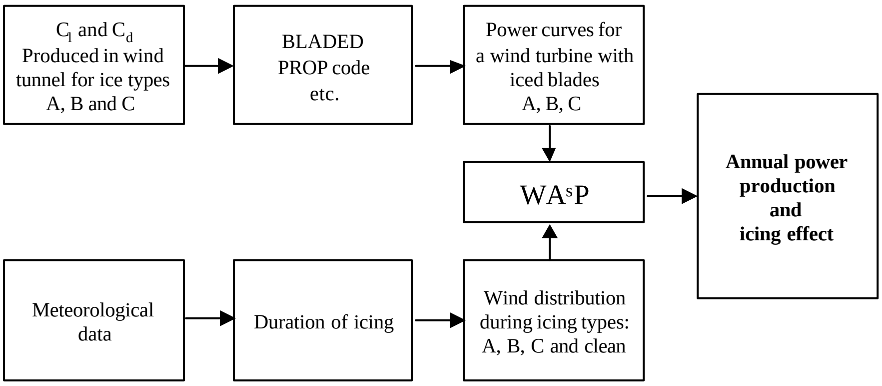


Figure 31. A schematic presentation of the procedure to calculate the power production at a planned site if the blades were partly clean and part of the year affected by various types and amounts (A, B, C) of ice.

The C_l and C_d values for various ice types and the power curves produced by the PROP code were used to calculate the effect of icing on power production at various sites in Europe. To calculate the duration of icing meteorological data was used, as shown schematically in Figure 31. In the following some examples are given [18].

The duration of icing and distribution of wind speed during different types of icing varies from site to site as shown in Figure 32.

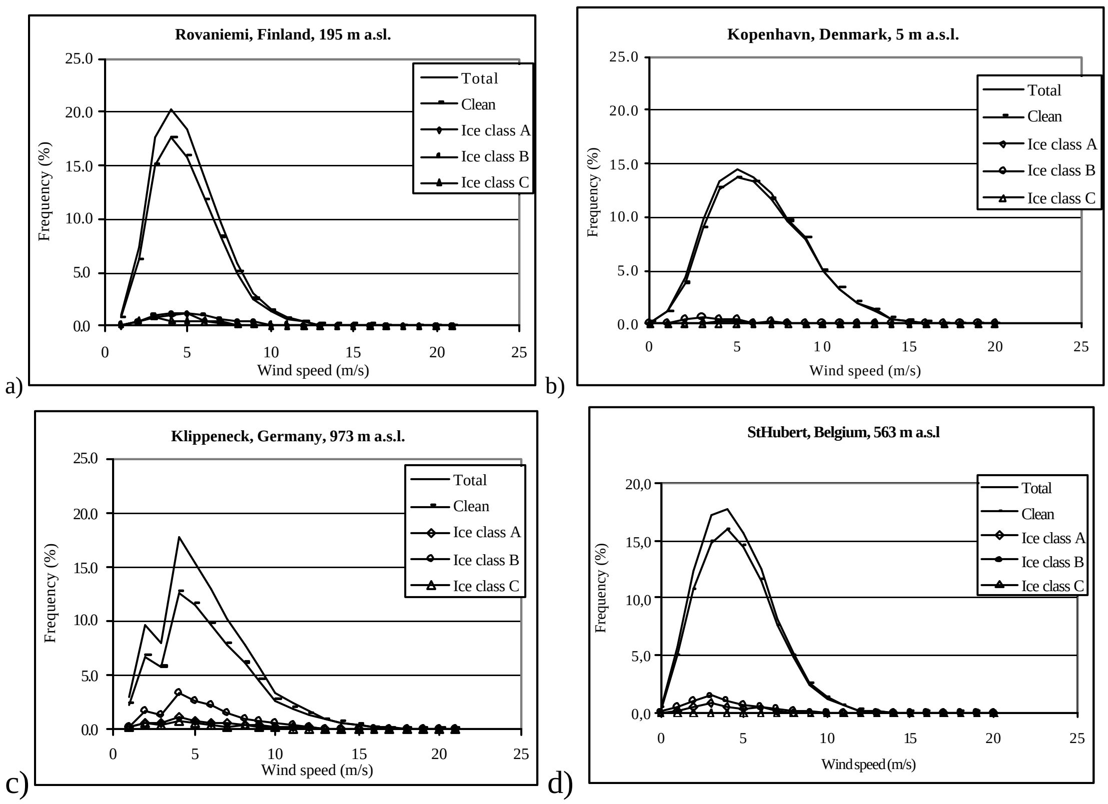


Figure 32 a-d. Wind speed distribution for non icing and three types (A, B, C, D; see figures X and Y) of leading edge icing at four weathers stations in various parts of Europe during the winters 1991-1996 [18].

Typically the icing effect at slightly ice affected sites on annual wind power production is about 1-10 %, and at harsh areas about 20-50 % [18], [31].

5.7 Heated blades

Heating of the blades is one possibility to avoid the icing incidents. So far the use of anti-icing system based to heating has been studied further, as no coating materials which can remain on the surface of a wind turbine blade for a long time seem to be available. Painted siliconous cover material has good ice repellent properties, but after quite a short period on operating turbine blade it becomes porous and not ice repellent any more. However, at lower latitudes, where lots of solar energy is available, the effect of icing can be decreased e.g. by using blades painted black. During the night black blades will be iced to the same degree as blades of other colours. During the day absorption of solar radiation, and thus the warmth of the blades will melt the ice, if the amount of ice is small. Heating and black color of the surface to prevent icing is not actually a new idea, and has been used (e.g. for wind measurements) since 1980´s [36].

Theoretical and empirical results show that the actual power demand to keep the blades ice free under operation (ice accreted upon the leading edge) is much less than earlier expected.

Table 1. Blade heating power in different heating system applications.

Application or Reference	Heating Power kW/m (blade length 12 m)	Max. Power (P=220 kW, Æ=25 m)	Relative Heating Power
First theoretical assumption [33]	1,2 kW/m	43 kW	20 % of nom. Power 10–15 % of gross prod.
First application, Pyhätunturi 1993	0,75 kW/m (6 m length, no tip)	13,5 kW	6 % of nom. Power 3–4 % of gross prod. Production losses at the tip area
Pyhätunturi 1994	0,5 kW/m (7 m length, including tip area)	10.5 kW	5 % of nom. Power 3 % of gross prod. Production losses
Pyhätunturi 1995	0,5 kW/m (7 m length, including tip area and fish piece)	11 kW	5 % of nom. Power 1 - 3 % of gross prod.
Pyhätunturi 1997	0,5 kW/m (9 m length, including tip area and fish piece, integrated)	14 kW	6 % of nom. Power 1 - 3 % of gross prod.

Partly as a result of the WECO project the Kemijoki Arctic Technology (KAT) published a commercial blade heating system, the JE-system [34], [35].

5.8 Special needs for WTs operating under icing conditions

Some special needs for wind turbines designed for cold climate operation were found:

- Heated anemometers for all sites with even only slight icing are necessary
- Information system of existing icing events
- Heated blades for extreme or frequent icing conditions

- Heating systems for control system gear box and hydraulics and possibly other components within the nacelle (f. ex. yaw system).
- Suitable lubricants for main bearings, gearbox, generator bearings. Special oil for hydraulic system.
- Cold resistant steel for all structural members with welds (mainly the tower).

5.9 Information policy of the WECO project

The WECO project as whole and each partner separately have been very active to produce deliverables to the use of the industry, manufacturers, utilities, operators, insurance companies, planners, research bodies etc.. The results have been presented e.g. in two international conferences the BOREAS III and IV conferences in northern Lapland, in the WOWECO II workshop for manufacturers took place in Wilhelmshaven, Germany in June 1997 and at EWEC´97 and at EWEC`99. Up to now the WECO project has produced 91 published papers.

The industry and potential wind turbine operators from different European countries, not participating the WECO project, and several authorities have contacted the coordinator and other partners about results and achievements of the project during the project and after its end. Thus the information from the project to the industry has been good.

6 CONCLUSION

Icing of blades and other structures of wind turbine is a significant problem at icing affected sites in various parts of Europe. Icing of blades reduces the power production and causes safety problems for the turbines and the public. The severity of the icing problem depends on icing climate, frequency of icing events and on-site weather conditions.

Interest in the icing problems and in methods to solve them and to predict the icing effect on loads, power production etc. has increased significantly during the WECO project. The increase of interest is strongly related to the fact that more and more power plants are planned to be installed in the far north, at inland and mountainous sites in Europe and else where. It is also predicted that a significant part, 10-20 % of the wind power plants erected to fulfil the demand of 40000 MW installed wind power in Europe by the year 2010 will be at regions where icing has to be taken into account in design of the wind turbines, their components like e.g. wind sensors and production of wind power production.

The WECO project has produced and distributed a lot of new information concerning wind energy production in cold climates and especially under icing conditions:

Very little has been known about icing and especially icing effect on meteorological measurements and win power production. The European icing map is the first scientific attempt to describe the icing climate in Europe. To produce the Icing map data from about 120 synoptic observation stations operated by national weather services was used. It may be said, that the Icing map is not a complete description of icing, but it gives a good basic information on duration of icing events, intensity of rime accretion and variation of in-cloud icing with height above the sea level at various parts of Europe.

The ice map combined with the European Wind Atlas is a proper tool for more precise prediction of annual energy production at cold and ice affected sites in Europe. These preliminary results provide basis for practical recommendations to be given to national meteorological services in order to produce more reliable data on atmospheric icing.

Several WECO test sites (wind power plants) located in various parts of Europe and operated under various types of icing condition provided experimental data. Large temperature differences as well as the combination of low temperatures and high wind speed, affecting the power curves and human risks during the maintenance, were studied identified as targets for further investigation.

Reliable wind measurements are essential for the prediction of wind energy potential as well as for the operation of wind turbines. The WECO project produced new theoretical and experimental results on icing effect on anemometers and measured wind speed. It is evident that no-ice-free anemometers can not be used for meteorological measurements and wind power purposes at ice affected sites. Thus the markets for reliable ice-free anemometers will be very large only in Europe in the next decade. According to the market survey performed it is obvious that at present only a few ice-free anemometers and three component sonic anemometers, but no ice-free vanes are available on the markets. Thus there is a need to improve the wind gauges for various purposes within the field of wind energy and meteorology.

Ice detectors, or other methods to detect ice, are essential for operating the wind turbines under heavy icing and frequent icing conditions as well as for meteorological institutes that try to provide icing data. Ice detectors available were tested at various WECO sites, and it was shown that use of ice detector will significantly increase information of icing, and that they are useful also e.g. for operation of blade heating systems. The market survey proved that the number of ice detectors available is very limited and at present the price of ice detectors is still quite high. Thus it is obvious that also other methods to detect ice have to be investigated.

To study the icing effect of loads and power production the main work has been done in improving the basic theoretical codes. To produce experimental data proved to be more difficult than expected, which thus leaves a need for further demonstrations. To study the icing effect on blades new C_l, C_d values for several iced profiles were produced using wind tunnel simulations. The PROP code was then improved to calculate the icing effect on power production under various types of icing conditions.

At present the estimated losses in power production at relatively heavily or very heavily ice-affected sites is estimated to be in the range of 20-50 per cent of the annual wind energy production. There is a need to improve de-icing and anti-icing systems for various parts of the wind turbines to decrease the losses due to low temperature and icing of various parts of the wind turbines and the control systems.

Codes used for load predictions were improved and analysed. The load predictions were verified to experimental data obtained during the project. It is shown, that operation under heavy icing conditions is not recommended. It was also shown that icing increases fatigue loads because additional ice masses cause higher deterministic loads, assymmetric masses on blades cause unbalance, edgewise vibrations will be increased and resonance may occur due to changed natural frequencies of components such as rotor blades. Icing of wind vanes may cause yaw errors and unexpected loads etc.

Ice throw from rotating blades is an important safety problem especially when the site of the wind power plant is planned to be close to public roads, housing, power lines, ship routes etc. Ice throw was studied using both theoretical models and experimental data collected e.g. using a questionnaire sent to operators in various parts of Europe and making observations at the WECO test sites. According to the results from the studies it was recommended, that for sites with high probability of icing the distance between the turbine and nearest object ought to be 1.5*(hub height + rotor diameter). An hilly and mountainous sites also the effect of slopes has to be taken into account.

At strongly ice affected sites public safety concerning ice throw and power production can be improved by using blade heating system to avoid icing of the rotor blades. Blade heating system has been studied theoretically and experimentally to optimise the heating demand and aerodynamical properties of the blades. During the WECO project the demand of heating power used for a anti-icing system at harsh conditions has been reduced to a fraction from what it was expected to be. As a result a commercial blade heating system is presented.

As a summary it may be noted, that icing may be a severe problem for wind power production and public safety close to wind turbines operated under icing conditions. Thus as a result from various parts of the WECO project recommendations have been worked out for the planning of wind energy plants at ice affected sites.

The interest in icing effect of wind power production and meteorological measurements, icing of structures and in observations/measurements and prediction of atmospheric icing has increased significantly among manufacturers, wind turbine operators, utilities, meteorological services, research units, consultants etc. located in the EU member countries, but also elsewhere, during the WECO project. Thus also the use of the results is growing strongly. To transfer information of the results successfully and without a delay to users and e.g. public authorities, the WECO project produced 91 published papers.

7 EXPLOITATION PLANS AND ANTICIPATION BENEFITS

Pre-competitive information about operation of wind turbines at ice endangered and low temperature sites in Europe has been transferred to various groups in industry, utilities, public authorities and developers. The information and the recommendations concerning cold climate operation of wind turbines given by the WECO project will stimulate the exploitation of wind energy utilisation in many areas of Europe where the potential is proved but the risk of an economic project is not yet calculable.

Tools have been developed, verified and partly commercially applied (at DEWI) in the field of public safety, namely prediction tools for ice throw. The service to predict the distance of ice fragments thrown off from operating wind turbines depending on rotor speed wind speed and wind direction is offered to wind farm developers and public administrations.

Methods and codes have been developed to assess the aerodynamic characteristics of various iced airfoils. The service to estimate aerodynamic loads and power curves of any iced rotor blade is offered to industry. Partly these tools have been verified by experiments (e.g. loads and power curve at the INVENTUS 6 turbine). The method is used as a commercial tool at DEWI, Risoe, VTT and Garrad Hassan.

The tool to predict the iced airfoil characteristics has been successfully applied for a rotor blade under commercial conditions (for the Garrad Hassan rotor blade design) at the end of the WECO project.

The improved blade element theory code “PROP code” together with the method to predict loads and power curves of iced blades is used by DEWI and FMI.

This is all approved by the sound activity list, where these contacts to interested groups are documented. In Germany the distance recommendations are more or less fixed by the values given by WECO recommendations. Also the recommendation that dependent on the wind direction and wind speed at which the wind turbines should be switched off or not at icing conditions is accepted by many public administrations.

The project proved the need for heated anemometers to be used in much wider regions in Europe than earlier expected. As an example the Vaisala Oy, which is one of the most important manufacturer of meteorological instruments, has adopted the results from the WECO project by releasing a new version of heated cup anemometers WAA25, which was also presented for the wind turbine manufacturers in the European Wind Energy Exhibition in Nice 1999. Also other companies have started to produce ice-free anemometers. Additionally, following the WECO recommendations, a lot of ice-free instruments are being ordered (market stimulation). Also the national meteorological services are today more interested in using ice-free anemometers for their meteorological measurements, to improve the quality of observation.

The blade heating system was further developed by Kemijoki Oy. The company presented the commercial system at the BOREAS IV conference in 1998. The system is today available for BONUS wind turbines. The blade heating system is already used at new wind power plants in Finland and Sweden, and up to now there are proposed power plants using this system at least in the Nordic countries but also in Austria, France, Germany and Switzerland, and other countries outside Europe. The blade heating system (JE-system) is today sold by the Kemijoki Arctic Technology Ltd (KAT).

The market study concerning heated anemometers is available at the FMI.

The Labko ice detector was operated by the WECO partners, and the results achieved were used by Labko for improvement of the detector. Today the Labko ice detector is available and is an essential part of the KAT JE-system. It has also been presented to the aviation authorities to be used at airports, and to Vaisala Oy to be used for the automatic weather observation systems.

The FMI has created a commercial product for the prediction of on-site in-cloud icing, up to now it has been applied in the of practically new wind power sites in Finland. This is also true for coastal regions, where icing has not been an essential problem for medium sized wind turbines, but will be a problem for large turbines reaching up to 100 m and more. Ice predictions have also been commissioned by other countries like Sweden, Germany, Austria, Chile, Canada, China etc.. However, the lack of sufficient data and the missing permission to use existing data caused problems up to now.

The know-how and results concerning icing, and especially in-cloud icing, produced and published by the WECO project were already being used commercially by the FMI for the EUMETNET SWS project, where the European meteorological services achieved new information on icing of meteorological sensors. This has led to a new commercial project to produce new requirements and specification for measurements operated under icing conditions. The information provided by the FMI has already led to changes in specifications of automatic weather stations produced by various manufacturers in different parts of the world.

Certification bodies have been regularly informed about the results in order to modify or verify the design load assumptions and to improve Standards and recommendations.

A large number of building authorities and public administration have been informed and some wind energy projects could be realised by clearing up concerns due to ice throw. Given recommendations by the WECO project, better planning of projects at ice endangered inland sites helped in exploiting wind energy projects.

All in all the sensitivity of industry concerning cold climate operation has been improved and more reliable load assumptions and safety in planning of projects at ice endangered sites has been initiated by the WECO project and thus has helped to improve safety and economics of wind energy and has launched wide planning and building of wind power plants at hostile and extreme climatic areas, where no successful wind projects had been thought practicable, in larger parts of Europe. At present the European wind energy industry and manufacturers of anemometers and ice detectors, as well as consultants and research institutes, have an advance on the strongly expanding worldwide markets on “cold climate wind turbines”.

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9 REFERENCES

[1] Seifert, H. and Tammelin, B.,1996. Icing of wind turbines. Final Report; JOU2-CT93-0366. Deutsches Windenergie-Institute, Finnish Meteorological Institute – Wilhelmshaven.

[2] Seifert, H. and Tammelin, B., 1996. Icing of wind turbines. In the proceedings of the European Union Wind Energy Conference 20-24 May in Gothenborg, Sweden. p. 1059- 1062

[3] Tammelin, B., Peltomaa, A., Hyvönen, R. and Säntti, K., 1996. Icing Effect on Wind Measurements and Wind Energy Potential Prediction. In: Tammelin, B. et al (eds.), BOREAS III, Proceedings of an International Meeting, 19-21 March, 1996, Saariselkä, Finland. Finnish Meteorological Institute. Helsinki p. 210-250.

[4] Tammelin, B. and Säntti, K., 1996. Estimation of Rime Accretion at High Altitudes – Preliminary results. In: Tammelin, B. et al (eds.), BOREAS III, Proceedings of an International Meeting, 19-21 March, 1996, Saariselkä, Finland. Finnish Meteorological Institute. Helsinki p. 194-209.

[5] Makkonen, L., Marjaniemi, M. and Peltola, E., 1997 Calculation of ice accretion on wind turbine blades. In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 615-618.

[6] Seifert, H. and Richert, F., 1997. Aerodynamics of iced airfoils and their influence on loads and power production. . In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. 458-463.

[7] Morgan, C., Bossanyi, E. and Seifert, H., 1998. Assessment of safety risks arising from wind turbine icing. In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 141-144.

[8] Tammelin, B., Morgan, C., Peltomaa, A and Hyvönen, R., 1997. Ice free anemometers. In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 389-392

[9] Tammelin, B. and Säntti, K., 1997. Icing in Europe. In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 393-396.

[10] Tammelin, B., Morgan, C., Peltola, E., Richert, F., Seifert, H., Säntti, K. and Vølund, P., 1997. Wind energy production in cold climate In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 347-353.

[11] Tammelin, B., Cavaliere, M., Kimura, S., Peltomaa, A. and Morgan, C., 1998. Ice free anemometers. In: Tammelin, B. et al (eds.), BOREAS IV, Proceeding of an International Meeting, 31 March – 2 April, 1998, Hetta, Finland. Finnish Meteorological Institute. Helsinki. p. 239-252.

[12] Kimura, S., Tammelin, B. and Peltomaa, A., 1998. Appendix in the final report of the EUMETNET SWS project. Finnish Meteorological Institute, Helsinki.

[13] Tammelin, B., Seifert, H. and Diamantaras, K.. BOREAS IV. DEWI Magazin Nr. 13, August 1998, DEWI, Wilhelmshaven, p. 67 – 70.

[14] Mertens, K., 1998. Wind energy production in cold climate. Arbeitsgemeinschaft für dezentrale energieversorgung (ADEV), CH-4410 Liestal. Report. 48 p.

[15] Tammelin, B., Joss, J. and Haapalainen, J., 1998. The Final report on the EUMETNET project "Specification of Severe Weather Sensors". Finnish Meteorological Institute, Helsinki.

[16] Tammelin, B. and Seifert, H., 1999. Wind energy production in cold climate. In: Proceedings of the EWEC, Nice, France 1 – 5 March 1999. p. 1005-1008.

[17] Tammelin, B., Böhringer, A., Cavaliere, M., Holttinen, H., Morgan, C., Seifert H. and Säntti, K. 1999. Wind Energy Production in Cold Climate. Final Report, JOR3-CT95-0014. Finnish Meteorological Institute, Helsinki.

[18] Tammelin, B., Kimura, S., Säntti, K. and Seifert, H., 1999. Icing in Europe - Effect upon wind power production. In: Proceedings of the EWEC, Nice, France 1 – 5 March 1999. p. 1051- 1054.

[19] Seifert, Henry; Schloz, Cornelia, 1990. Additional loads caused by ice on rotor blades during

operation. - European Community Wind Energy Conference: proceedings of an international conference held at Madrid, Spain 10-14, September 1990. - Bedford: Stephens and Ass., 1990, p. 203-207.

[20] Seifert, H., 1996; Rotorblätter, eiskalt erwischt (Glacial Period for Rotor Blades), DEWI-Magazin, No 8, pages 4 – 13.

[21] Richert, F. and Seifert, H., 1997. Eis im Kanal. DEWI-Magazine 10, p. 4-13.

[22] Horbaty, R. ENCO Langenbruck, Switzerland: Development of Wind Energy in Alpine Regions. In: Proceedings of the EWEC, Nice, France 1 – 5 March 1999. p. 531-533.

[23] Eggelston, D. M.; Stoddard, F. S.: Wind Turbine Engineering Design, New York: Van Nostrand Reinhold, Library of Congress Catalog Number 86-23331, 1987

[24] Hulle, F. J. L., et al., 1996. Verification of Design Loads for Small Wind Turbines, Final report JOULE II Project CT93-0423, ECN, Petten, Netherlands.

[25] Kenyon, P. R., 1994. Anemometry in New England mountain icing environments. In: Tammelin, B. et al (eds.), BOREAS II, Proceeding of an International Meeting, 21-25 March 1994, Pyhätunturi. Finnish Meteorological Institute. Helsinki, p. 154-163.

[26] Vølund, P. and Antikainen, P., 1997. Ice-Induced Loads on Wind Turbines. In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 464-467.

[27] Stuke, M. 1998. Estimation of effect of icing on power production for stall and pitch controlled wind turbines – Diploma thesis. Finnish Meteorological Institute, Helsinki, Finland. p.72.

[28] Tammelin, B. Stuke, M., Seifert, H. and Kimura, S., 1999. Icing effect on power production of wind turbine. In: Tammelin, B. et al (eds.), BOREAS IV, Proceeding of an International Meeting, 31 March – 2 April, Hetta, Finland. Finnish Meteorological Institute, Helsinki.

[29] Walker, S.N., 1976. Performance and optimum design analysis and computation for propeller type wind turbines. (Diss.) Oregon State University.

[30] Hibbis, B. and Radkey, R.L., 1983**.** Calculating rotor performance with the revised PROP computer code. Aero Vironment, Inc., Pasadena, CA.

[31] Botta, G., Cavaliere, M. and Holttinen, H., 1998. Ice accretion at Acqua Spruzza and its effect on wind turbine operation and loss of energy production. In: Tammelin, B. et al (eds.), BOREAS IV, Proceeding of an International Meeting, 31 March – 2 April, 1998, Hetta, Finland. Finnish Meteorological Institute, Helsinki. p. 77-86.

[32] Tammelin, B., 1982. Frost formation on anemometers and frost prevention experiments. Technical report No 26. Finnish Meteorological Institute. 34 pp.

[33] Böhmeke, G., 1991. Wind power plants in the weather conditions of Northern Finland. Technical Research Centre of Finland, Research Notes 1354. Espoo, Finland.

[34] Peltola, E., Marjaniemi, M., Kaas, J. and Aarnio, E., 1997. Heating of Wind Turbine Blades - Design and Operational Experience. In: EWEC'97, Proceedings of the International Conference, Dublin, Ireland, October 1997. p. 619-621.

[35] Peltola, E., 1999. Prospects of Arctic wind technology and wind farm development in Finland. In: Proceedings of the EWEC, Nice, France 1 – 5 March 1999. p. 485-487.

[36] Tammelin, B., Roos, I.and Hyvönen, R. 1999. Wind energy production in cold climate. Final report. ERBIC20CT960001. 16 p.

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http://www.fmi.fi/TUT/MET/energia/WECO.html