

# PERMITTING SETBACK REQUIREMENTS FOR WIND TURBINES IN CALIFORNIA

*Prepared For:*

**California Energy Commission**  
Public Interest Energy Research Program

*Prepared By:*

**California Wind Energy Collaborative**



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## Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environment Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

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## Abstract

The California Wind Energy Collaborative was tasked to look at barriers to new wind energy development in the state. Planning commissions in the state have developed setback standards to reduce the risk of damage or injury from fragments resulting from wind turbine rotor failures. These standards are usually based on overall turbine height. With the trend toward larger capacity, taller towers and longer blades, modern wind turbines can be “squeezed out” of parcels thus reducing the economic viability of new wind developments.

Current setback standards and their development are reviewed. The rotor failure probability is discussed and public domain statistics are reviewed. The available documentation shows rotor failure probability in the 1-in-1000 per turbine per year range. The analysis of the rotor fragment throw event is discussed in simplified terms. The range of the throw is highly dependent on the release velocity, which is a function of the turbine tip speed. The tip speed of wind turbines does not tend to increase with turbine size, thus offering possible relief to setback standards. Six analyses of rotor fragment risks were reviewed. The analyses do not particularly provide guidance for setbacks. Recommendations are made to use models from previous analyses for developing setbacks with an acceptable hazard probability.

**Keywords:** Wind turbines, wind power, wind energy, permitting, zoning, ordinances, hazards



# Executive Summary

## Introduction

California counties have adopted setbacks for wind turbines primarily to account for the risk of fragments from the rotor. These setbacks are usually based on overall turbine height, which includes the tower height and the radius of the blade. With evolution in the industry to larger turbines, these setbacks increase in total distance and become a hindrance to wind energy development. The authors present a hypothetical example where the total energy production of a windplant is reduced with the application of larger, modern turbines.

## Purpose

The purpose of this report is to summarize wind turbine setbacks in California and to describe any connection between rotor failure and windplant setback requirements.

## Project Objectives

The objectives of this study of wind turbine setbacks were to:

- Document and compare current wind turbine setbacks in California
- Report on how the setbacks were developed
- Report on the probability of rotor failure
- Study existing analyses of the rotor fragment hazard and determine if setback criteria can be developed with existing information.

## Project Outcomes

The outcomes of the project were:

- The authors gathered information regarding turbine setbacks by interviewing county planning personnel, studying the county ordinances, and conducting a literature search of the subject. Wind turbine setbacks were documented for California counties with existing and future wind energy development, including Alameda, Contra Costa, Kern, Merced, Riverside, and Solano counties. Comparisons were made between the various ordinances.
- From this data the authors developed a picture of how the turbine setbacks were established. The majority of the ordinances were developed by ad hoc groups of local interests and the fledgling wind energy industry.
- The authors conducted a literature survey regarding the probability of rotor failure. Several sources of information were obtained. These include failure reports of turbines in Alameda County, failure data from Denmark and Germany reported in the WindStats periodical, and a Dutch report on European rotor

failures. The probability of rotor failure varied from 1-in-100 to 1-in-1000 turbines per year.

- The authors present a simplified analysis of the rotor fragment hazard to compare to more complex analyses. The analyses of six researchers were found in a literature survey of varying complexity. Results were compared to determine if setback criteria could be developed.

## Conclusions

Wind turbine setbacks vary by county. The counties typically base the setback on the maximum of a fixed distance or a multiple of the overall turbine height. A common setback is three times the overall turbine height from a property line.

There is no evidence that setbacks were based on formal analysis of the rotor fragment hazard.

The most comprehensive study of wind turbine rotor failures places the risk of failure at approximately 1-in-1000 turbines per year.

The maximum range of a rotor fragment is highly dependent on the release velocity that is related to the blade tip speed. Tip speed tends to remain constant with turbine size; therefore, the maximum range will tend to remain constant with turbine size. In the analysis of rotor fragment trajectories, the most comprehensive models yielded results that showed the shortcomings of simpler methods. Overall, the literature shows the possibility of setbacks for larger turbines may be based on a fixed distance and not the overall height.

## Recommendations

The authors recommend that a comprehensive model of the rotor fragment hazard be developed based on the results of the literature review. This tool would then be used with a variety of turbine sizes with the objective to develop risk-based setback standards.

## Benefits to California

The information provided in this report can be used by California planning agencies as a background for evaluating wind turbine setbacks. Researchers can also use the information as background for developing models of the rotor fragment hazard.

## 1.0 Introduction

### 1.1. Background and Overview

California has played a pivotal role in the creation and evolution of the wind-based electric power generation industry. Wind power is unique in the visibility and exposure to the public as compared to other forms of power generation. By necessity, communities have become involved in planning for the development of wind power in their jurisdiction. Both the regulation and technology of wind power evolved together in the last two decades.

Particular attention was made to protect the public from hazards. With the advent of a new technology, the probability of failure tends to be higher because the physics are not well understood. The engineering of the technology must also be balanced with economics, and the balance is very tenuous at the beginning of a new venture. Equipment and business failures plagued the industry in the last two decades, and legacy equipment still fails at a relatively high rate today.

One hazard possibility of wind turbines is the failure of a portion of the rotor resulting in fragments being thrown from the turbine. Concerns over public exposure to this risk led the counties to develop setbacks from adjacent properties and structures. The development of county ordinances took place independently of each other; however in most cases the fledgling wind power industry was involved in the development (McClendon and Duncan 1985). In general, the setbacks were based on the heights of the turbines.

Utility scale turbines installed in California have evolved from 50 kilowatt (kW) machines of 25 meter (m) overall height to 3.0 megawatt (MW) machines of 126 m overall height. The nature of that evolution, in general, is that manufacturers stop production of smaller turbines due to improved economics of the new larger turbines. With increased overall height, the setback distance is increased, and modern turbines can be “squeezed out” of developments.

The California Wind Energy Collaborative (CWEC, <http://cwec.ucdavis.edu/>), through its “Windplant Optimization” task, was directed to prepare this white paper on permitting issues in regards to the rotor fragment risk. The concern over restrictions on development was the impetus to study current ordinances and the rotor fragment risk. Two possibilities offer the potential for relief in this area. Modern wind turbines might offer higher reliability, thus lowering the risk of rotor failure. Second, in the event of a rotor failure, the hazard area is governed by the blade tip speed. The tip speed tends to remain constant with turbine size. Therefore, more appropriate setbacks might be a fixed distance, and not a function of the turbine size. These possibilities, along with background research, are discussed in this report.

## 1.2. Example Windplant and the Problem with Current Setbacks

Setbacks are established to minimize risk of damage or injury from component failure on property and personnel. The setbacks are usually a multiple of the total turbine height, from tower base to upper extreme point of the rotor (see Figure 1). Generally the setbacks can vary from 1.25 to 3 times the overall machine height. Larger setbacks are sometimes required for special areas. In contrast to these standards, counties in California with more rural development, such as Merced and San Joaquin, use building setbacks and do not distinguish wind turbines separately.

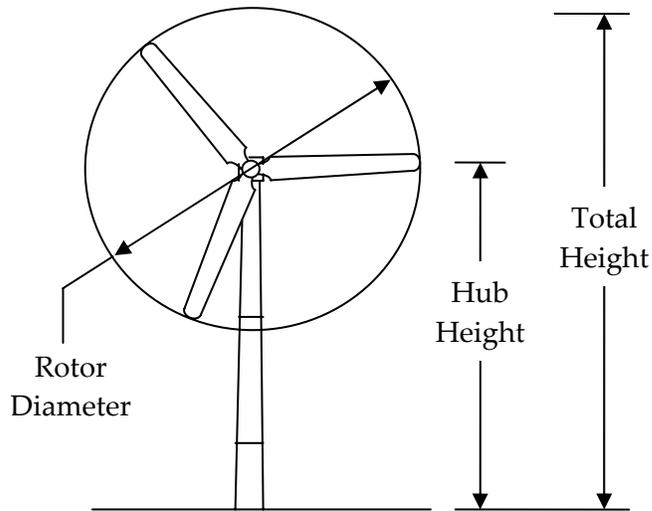


Figure 1. Wind turbine dimensions

As an illustration of the potential of setbacks limiting modern wind energy development, consider the following hypothetical situation. A developer has a 1000 by 1000 m (1 square kilometer or 247 acres) parcel of land available in a county requiring a setback three times machine total height. The site has a strong prevailing wind direction, and the machines are to be spaced in consideration of wake effects of 3 diameters crosswind and 10 diameters downwind. Two machines are considered:

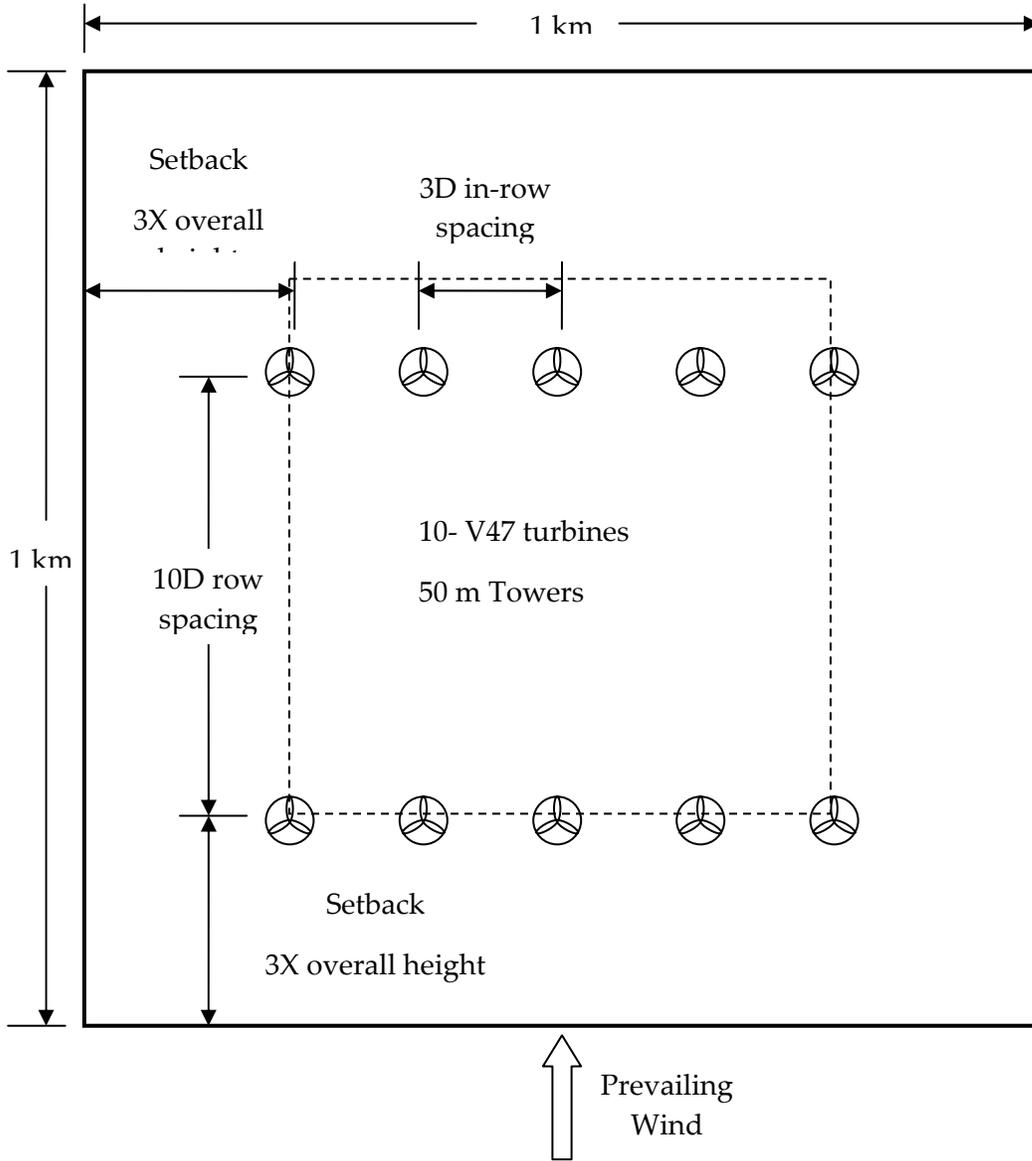
### 1.2.1. 1. **Vestas V-47**

- 660-kW full rating
- 47 m rotor diameter
- 50 m tower height

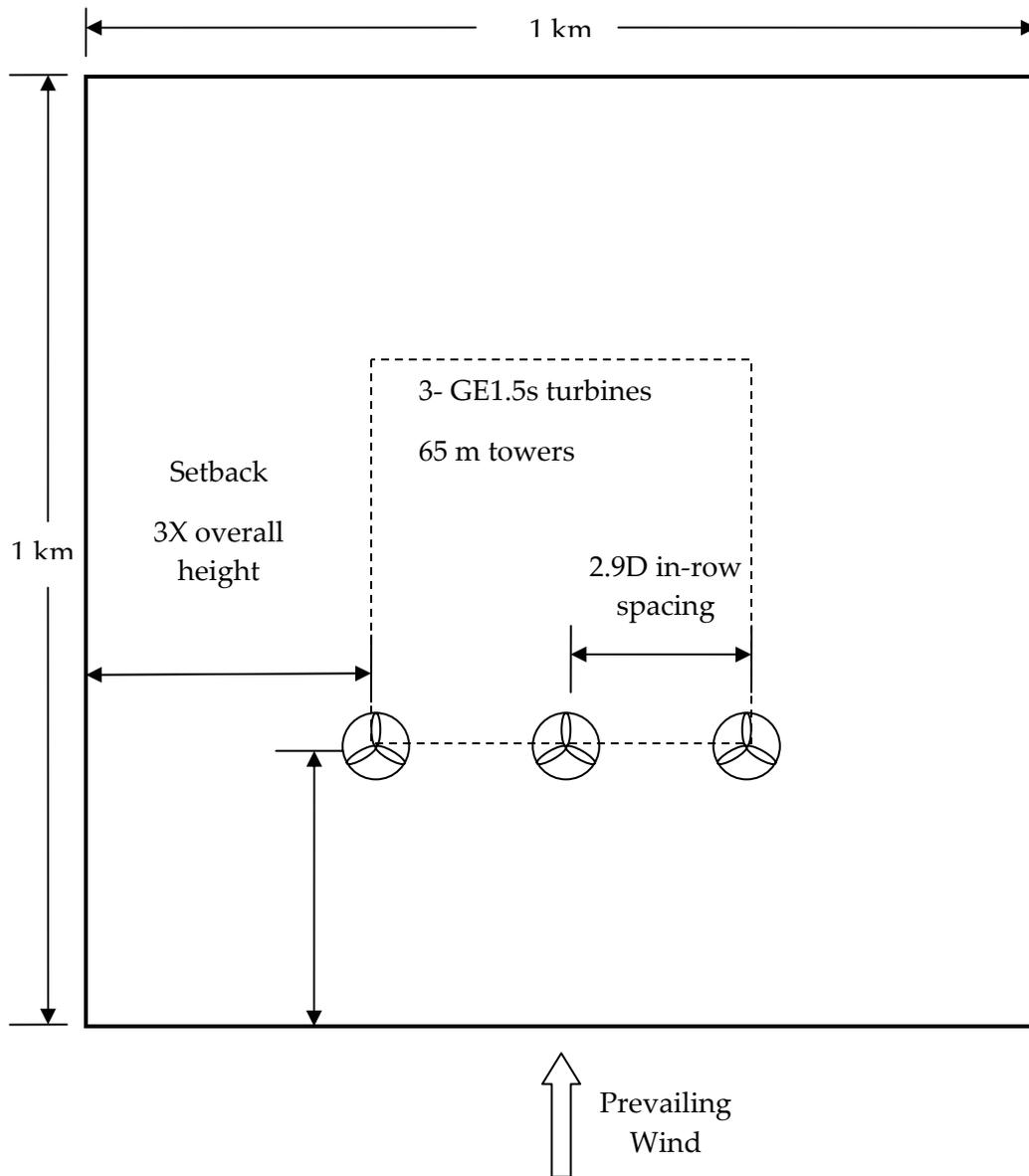
### 1.2.2. 2. **General Electric GE 1.5s**

- 1500-kW full rating
- 70.5 m rotor diameter
- 65 m tower height

The layouts are shown in Figure 2 and Figure 3, with shaded zones representing the setback areas. The overall height is the sum of the tower height plus half the rotor diameter.



**Figure 2. Layout for V-47 wind turbines based on setback requirement of three times total turbine height**



**Figure 3. Layout for GE 1.5s machines based on setback requirements of three times total turbine height**

For the V47 machine, the spacing requirements and setbacks allow for 10 machines with total rating of 6.6 MW. In contrast, the requirements allow only three GE 1.5 turbines with total rating of 4.5 MW. The crosswind spacing in this case would probably be reduced slightly. Downwind spacing requirements would force a second row of turbines off the parcel. The setback requirements for this example result in lower energy production with the application of larger, modern machines. The options available to a

developer are further constrained with the current trend of manufacturers producing larger machines, and phasing out the production of smaller machines such as the V-47.

### **1.3. Project Objectives**

Project objectives for this study were to:

- Document and compare current wind turbine setbacks in California
- Report on how the setbacks were developed
- Report on the probability of rotor failure
- Study existing analyses of the rotor fragment hazard and determine if setback criteria can be developed with existing information.

Wind turbine setbacks are codified for reasons other than safety. Scenic corridors might be established so that views are not adversely impacted by new structures. Acoustic emissions from turbines might limit siting. Maximum sound pressure levels might be established at property lines or dwellings, constraining the placement of turbines. This report deals specifically with the issue of the rotor fragment hazard.



## 2.0 Project Approach

For each of the project objectives, the authors took the following approaches:

- Document and compare current wind turbine setbacks in California

The authors considered only counties with existing utility-scale wind power development. These counties are Alameda, Contra Costa, Kern, Merced, Riverside, San Joaquin, and Solano. The authors obtained the majority of the county ordinances from the Internet. Many counties have their codes residing on Ordlink (<http://ordlink.com/>), a LexisNexis product. All county planning departments were contacted for any additional information. In some cases, the wind energy ordinance was a separate document (Solano 1987) or part of an Environmental Impact Report (Alameda 1988b). The setbacks were organized into a tabular format for comparison.

- Report on how the setbacks were developed

The authors conducted interviews with county planning personnel on this topic. The authors also conducted a literature survey on the Internet and reviewed the conference proceedings of the American Wind Energy Association, the British Wind Energy Association, and the European Wind Energy Association.

- Report on the probability of rotor failure

The authors conducted a literature survey on this topic with the sources mentioned above, and searched the annual conference proceedings of the American Society of Mechanical Engineers technical conference on wind energy.

During the study, CWEC obtained records of Alameda County turbine failures. These data were compiled and analyzed. The authors also compiled failure data from European turbines reported in *WindStats*, a quarterly newsletter of Windpower Monthly. CWEC also translated and reviewed an interim report on rotor failures prepared by the Netherlands Energy Agency.

- Study existing analyses of the rotor fragment hazard and determine if setback criteria can be developed with existing information.

The authors conducted a literature survey with sources mentioned above, and developed a simple model of the rotor fragment hazard to outline certain characteristics of the problem. The method and results for each researcher is described. Where possible, the results are compared across analyses.



### 3.0 Project Outcomes

#### 3.1. Current Wind Energy Ordinances

The majority of the county ordinances were obtained from the Internet. The authors strongly suggest checking the current information available on the websites. Checking the requirements is especially important during the lifetime of a development project. Current ordinances and their safety setback requirements are summarized in Table 1.

**Table 1. Setback references in California county ordinances**

	Internet Site	Ordinance	Setback Reference
<b>Alameda</b>	Code for wind energy not available on internet	Draft Environmental Impact Report, Repowering a Portion of the Altamont Pass Wind Resource Area, Appendix A, Alameda County Windfarm Standard Conditions	Paragraph 15. Safety Setback
<b>Contra Costa</b>	<a href="http://www.co.contra-costa.ca.us/">http://www.co.contra-costa.ca.us/</a>	County Code, Title 8 Zoning, Ch. 88-3 Wind Energy Conversion Systems	88-3.602 Setback Requirements
<b>Kern</b>	<a href="http://ordlink.com/codes/kerncoun/">http://ordlink.com/codes/kerncoun/</a>	Title 19 Zoning, Chapter 19.64 WIND ENERGY (WE) COMBINING DISTRICT	19.64.140 Development standards and conditions
<b>Merced</b>	<a href="http://web.co.merced.ca.us/planning/zoningord.html">http://web.co.merced.ca.us/planning/zoningord.html</a>	Zoning Code (Ordinance) Ch. 18.02, Agricultural Zones	Table 5 Agricultural Zones Development Standards
<b>Riverside</b>	<a href="http://www.tlma.co.riverside.ca.us/planning/ord348.html">http://www.tlma.co.riverside.ca.us/planning/ord348.html</a>	Ordinance 348, Section 18.41, Commercial Wind Energy Conversion Systems Permits	18.41.d(1) Safety Setbacks
<b>Solano</b>	Code for wind energy not available on internet	Wind Turbine Siting Plan and Environmental Impact Report 1987	Page 17 Safety Setbacks

Table 2 compares setbacks for several of the counties organized by feature that the turbine must be displaced from, such as a property line. The distances are stated in multiples of overall turbine height (Figure 1). If a fixed distance is included with the multiple, then the maximum of the two values must be used for the setback.

**Table 2. Safety setback comparison. Note: for reference purposes only. Check counties for current zoning requirements.**

	Property Line	Dwelling	Roads	Reductions in Setbacks
<b>Alameda County</b>	3x/300 ft (91 m), more on slope	3x/500 ft (152 m), more on slope	3x/500 ft (152 m), 6x/500 ft from I-580, more on sloped terrain	maximum 50% reduction from building site or dwelling unit but minimum 1.25x, road setback to no less than 300 ft (91 m)
<b>Contra Costa County</b>	3x/500 ft (152 m)	1000 ft (305 m)	None	exceptions not spelled in ordinance can be filed with county
<b>Kern County</b>	4x/500 ft (152 m) <40 acres or not wind energy zone, 1.5x >40 acres	4x/1000 ft (305 m) off-site	1.5x	With agreement from adjacent owners to no less than 1.5x
<b>Riverside County</b>	1.1x to adjacent Wind Energy Zones	3x/500 ft (152 m) to lot line with dwelling	1.25x for lightly traveled, 1.5x/500 ft (152 m) for highly traveled.	None
<b>Solano County</b>	3x/1000 ft (304 m) adjacent to residential zoning, 3x from other zonings	3x/1000 ft (304 m)	3x	Setback waived with agreement from owners of adjacent parcels with wind turbines

Table 2 shows that counties have different requirements. Riverside County maintains the minimum setback distances to properties with adjacent wind energy zoning.

Alameda County has adjustments for sloping terrain. If the ground elevation of the turbine is two or more times the height of the turbine above the feature, the setback distance increases from three times to four times. With the exception of Riverside County, all allow for reduction of the setback distance with special consideration. The Altamont Repowering EIR (Alameda County 1998) is an example of a reduced setback, which resulted from a developer submitting a rotor fragment risk analysis as substantiation for the reduction.

Merced County has some wind energy development in the Pacheco Pass area, and utilizes standard building setbacks for wind turbines in agricultural districts. San Joaquin County has similar requirements for the development in the Altamont Pass area.

## **3.2. Setback Development**

With the exception of Solano County, the ordinances are not explanatory documents. Background information is not provided. The most comprehensive paper on the subject of wind energy permitting in California comes from McClendon and Duncan. Although this paper was written in 1985, it captures the essence of the process at the time and generally, not much has changed in the interim. Another paper by Throgmorton (1987) focuses on Riverside County development exclusively. Further clues to the development of standards are found in Environmental Impact Reports written for the counties on specific developments. The counties are discussed separately below.

References in the literature to safety setbacks are scarce. One is found in Taylor (1991). Taylor proposed setbacks for a 30 m diameter rotor machine, but no tower height is mentioned. The proposed setbacks were 120–170 meters from a habitation or village, 50 meters from a lightly traveled road, and 100 meters from a heavily traveled road. A *Windpower Monthly* article regarding a rotor failure in Denmark (Møller 1987) mentions setbacks for safety. A setback of 90 meters plus 2.7 times the rotor diameter was proposed. The *Wind Energy Permitting Handbook* available from the National Wind Coordinating Committee (NWCC 2002) provides no guidance on setbacks. In all the above references, there is no discussion of the technical basis for the setbacks.

### **3.2.1. Alameda County Ordinance**

Alameda County, encompassing most of the Altamont pass, was one of the first regions in the world to have large-scale wind energy development. Until recently, the Altamont Pass area has been isolated from population centers, lowering the possibility of conflict with the community. The McClendon and Duncan paper (1985) reported that concerns over safety and reliability of wind turbines resulted in an ad-hoc public/industry group to develop new standards. The setbacks as they stand today are found in Resolution Number Z-5361 of the Zoning Administrator of Alameda County, dated September 5, 1984. There is no known technical description on how the setbacks were developed.

### **3.2.2. Contra Costa County Ordinance**

Contra Costa encompasses the northern portion of the Altamont pass. The zoning language is much less specific than Alameda County, but the setbacks are similar.

### **3.2.3. Kern County Ordinance**

According to county personnel and McClendon and Duncan (1985), the standards for Kern County were developed with an ad-hoc committee of wind energy people and other interests, as in the case with Alameda County. Kern has stricter setbacks for properties not zoned for wind energy development, but is less restrictive for roads (see Table 2).

### **3.2.4. Riverside County Ordinance**

Riverside County is an area of intense development. Regulations were established after an extensive Environmental Impact Report (EIR) by Wagstaff and Brady (Riverside County California, United States Bureau of Land Management et al. 1982). Clues to the majority of the setback distances are in the report. Although there is no technical basis for the original setback of three times the total height of the turbine, one can infer that this distance arose from the discussion of wake effects. It was expected that in-row spacing for wake effects would be six diameters, and adjacent wind energy parcels would require a spacing of at least half this distance. The report also mentions an estimate of the fragment throw distance for the MOD-0A, an early Westinghouse machine. The stated value of 500 ft (152 m) translates to three times overall height for this turbine. Evolution of the ordinance resulted in reduction of some of the setbacks, which now seem to offer a buffer for the possibility of tower collapse.

### **3.2.5. Solano County Ordinance**

Solano County also developed wind turbine requirements with industry involvement in 1985. The outcome of this work was the Solano County Wind Turbine Siting Plan (Solano County 1987), which remains the guide for permitting in the county. The plan supercedes the current language in the zoning ordinance that has setbacks of 1.25 times the overall turbine height. This plan was developed by the authors of the Riverside County EIR, and proposes a “three times” setback. The estimated rotor fragment risk of the MOD-0A is again mentioned. There is a comparison of the setbacks with the rotor fragment risk of the MOD-2 turbine. The throw distance of this turbine in a vacuum was estimated to be 1300 feet (396 m, 3.7 times overall turbine height) for a broken tip and 700 feet (213 m, 2 times overall turbine height) for the whole blade. There is no technical discussion for these values and they are not tied into the proposed spacing. The Montezuma Hills EIR (Solano County and Earth Metrics 1989), proposed a three times diameter safety setback, with no consideration for turbine height. Neither reference provides a technical basis for the setback distance.

### 3.3. Rotor Failure Probabilities

This section discusses the probability of a rotor failure occurring. Probabilities will be discussed in terms of ratios. For example, a coin toss with heads has a one in two probability, represented equally as 0.5,  $\frac{1}{2}$ ,  $5 \times 10^{-1}$ . A probability of something occurring once in one-hundred trials can be represented as  $10^{-2}$ . The probability applied to rotor failures will be stated as the probability of failure for a turbine in one year of operation. A probability of  $10^{-2}$  per turbine per year can then be understood that on average there will be one rotor failure in a year for every 100 turbines.

Reporting on turbine failures is very limited, most likely due to the sensitivity of the industry. There are few accounts of turbine failure in the literature. There are statistics in the public domain that will be discussed below.

Types of rotor failures are as follows:

- Root-connection full-blade failure
- Partial-blade failure from lightning damage
- Failure at outboard aerodynamic device
- Failure from tower strike
- Partial-blade failure due to defect
- Partial-blade failure from extreme load buckling

Some of the causes of rotor failures:

- Unforeseen environmental events outside the design envelope
- Failure of turbine control/safety system
- Human error
- Incorrect design for ultimate loads
- Incorrect design for fatigue loads
- Poor manufacturing quality

Not surprisingly, most failures are a combination of these factors, which points to the complexity of the technology. The probabilities of some events are highly correlated with each other. For example, loss of grid power is highly correlated with high wind events. The potential then exists for a control system malfunction due to loss of power to coincide with a high loading event. Thus the turbine designer must plan for both events occurring simultaneously.

#### 3.3.1. Rotor Failures in the Literature

One of the earliest documented rotor failure events comes from one of the first applications of utility-scale wind energy (Putnam 1948). It is also one of the few accounts with a published distance. The Smith Putnam 1.25 MW turbine suffered a rotor failure in its test campaign resulting in a blade throw of 750 ft (230 m), or 3.7 times the overall height. The failure was attributed to lack of knowledge of the design loads for the

turbine. The blade throw was probably exacerbated by siting on a slope (approximately ten degrees). The blade was of steel construction, with a weight of eight tons (mass of 7260 kg). That is at least 50% heavier than modern construction. A heavier blade could fly farther due to a reduced drag-to-weight ratio (Eggers, Holley et al. 2001).

The next period of literature deals with the analysis of large-scale turbines under development in the 1970s and early 1980s. Although the possibility of failure was discussed, no mention of the probability was placed forward for the Department of Energy (DOE) MOD series turbines such as the General Electric MOD-1 (General Electric 1979) and the Boeing MOD-2 (Lynette and Poore 1979). The Solar Energy Research Institute (SERI) conducted a preliminary study of wind turbine component reliability (Edesess and McConnell 1979). Using an analysis of the individual failure rate estimates and inspection intervals of the rotor and braking systems, the authors predicted a failure rate for the wind turbine rotor at  $1.2 \times 10^{-2}$  per turbine per year.

A strong early wind program in Sweden prompted studies of the subject (Eggwertz, Carlsson et al. 1981) where the first attempts at analyzing the rotor fragment risk were made. The first guess at the probability of failure was made at 1 in 100,000 ( $10^{-5}$ ) failures per turbine per year.

The evolution of the wind industry back to smaller turbines brought large scale manufacturing and experience was gained with equipment failures. In a 1989 paper (De Vries 1989) conducted a blind survey of manufacturers that reported on 133 turbine failures in the industry. De Vries also placed probabilities at  $2 \times 10^{-2}$  rotor failures per turbine per year for the Netherlands,  $3$  to  $5 \times 10^{-3}$  for Denmark and  $3 \times 10^{-3}$  for the United States. This is two to three orders of magnitude higher than that predicted by Eggwertz, but closer to the SERI analysis.

Failures are occasionally reported in Windpower Monthly. They have reported a rotor overspeed failure in Denmark (Møller 1987) and full-blade failures in Spain (Luke 1995). A report in the technical literature comes from Germanischer Lloyd (Nath and Rogge 1991), one of the certification bodies for wind energy. The paper describes two medium-size turbine rotor failures. The rotor diameter and tower height were not reported. One failure was attributed to insufficient shutdown braking force resulting in overspeed, and blades were thrown to 150 and 175 meters. The other failure was attributed to poor manufacturing quality and blade fragments were thrown 200 meters. Updates to certification requirements were made as a result of the failure investigations. These certification requirements call for redundancy in safety shutdown systems and quality control in the blade manufacturing process. De Vries had also earlier suggested stricter certification requirements to reduce the rotor failure rate.

One wind turbine manufacturer has made a public testimonial of their rotor failure rate. A managing engineer at Vestas, in testimony for the Kittitas Valley Wind Power Project in Washington State (Jorgensen 2003), declared that there had been only 1 blade failure in 10,000 units for 12 years. The failure reported occurred in 1992 on a V39-500 kW

machine when a blade was thrown 50–75 meters. If an average of six years of total operation for the entire fleet is assumed, the failure rate would be estimated at  $1.6 \times 10^{-5}$  rotor failures per turbine per year.

### **3.3.2. Alameda County Turbine Failure Data**

Under Article 15 of the Alameda County Windfarm Standard Conditions (Alameda County 1998a), a windfarm operator must notify the County Building Official of any tower collapse, blade throw, fire, or injury to worker. Recent files of failure data from the county building department were compiled by the CWEC in order to determine failure rates. County representatives claim that not all operators have been diligent in their reporting, but one operator of Kenetech 56-100 machines has been. These turbines are 100 kW machines with 56 ft (17 m) diameter rotors. The majority were manufactured in the 1980s. The failure reports only indicate the failure type. There is no mention of rotor fragment distance (if fragments were thrown from the turbine), or the conditions at time of failure. The failures could have been discovered as the result of an inspection before any part had separated from the turbine. The failure data covered the year 2000 to fall of 2003. The number of Kenetech 56-100 machines in operation by this operator was obtained from the California Wind Performance Reporting System (<http://wprs.ucdavis.edu/>).

For the time period of the reports, the rotor failure rate was  $5.4 \times 10^{-3}$  failures per turbine per year. This value coincides well with that reported by De Vries (1989). As a comparison the failure rate for the tower was  $6.9 \times 10^{-4}$  failures per turbine per year, an order of magnitude less probable than the rotor failure rate.

### **3.3.3. WindStats Turbine Failure Data**

WindStats is a technical publication for the wind industry published quarterly in Denmark. Failure data are available for wind turbines located in Denmark and Germany. The Denmark data have been available since 1993; the Germany data since 1996. Like the Alameda County data, the data only indicate failure type. There is no mention of rotor fragment distance (if it occurred at all), or the conditions at the time of failure, are mentioned. CWEC compiled data through the spring 2004 issue.

For Denmark, the failure rate for rotors was  $3.4 \times 10^{-3}$  failures per turbine per year. Again, this is within the values reported by De Vries (1989) in the late 1980s. The tower failures for the same period are  $1.0 \times 10^{-4}$ . As with the Alameda data, the tower failure probability is an order of magnitude lower than the rotor failures. For Germany, the data are reported as “rotor” failures, which for the reporting period were  $1.5 \times 10^{-2}$  failures per turbine per year. This is an order of magnitude higher than the Denmark data, but on the same order of the Netherlands in De Vries. There are no apparent trends in the data indicating changes in failure rates over time.

### **3.3.4. Dutch NOVEM Report**

During the writing of this report the Netherlands Agency for Energy and the Environment (NOVEM) was writing a handbook on wind turbine siting due to the risk

posed by wind turbines. The overall report is summarized in English by Braam and Rademakers (2004) from the Energy Research Centre of the Netherlands, ECN, and the report was published in Dutch in 2005 (Braam, van Mulekom et al. 2005). The CWEC received approval from the authors to translate Appendix A of the handbook and it is included in Appendix A of this document.

The appendix from the handbook reviews data from two large databases of wind turbines in Denmark and Germany. The database covers turbine operation from the 1980s until 2001. The authors analyzed the data and recommended values of risk for the following failure events:

- Failure at nominal operating rpm  $4.2 \times 10^{-4}$
- Failure at mechanical breaking (~1.25 time nominal rpm)  $4.2 \times 10^{-4}$
- Failure at mechanical breaking (~2.0 time nominal rpm)  $5.0 \times 10^{-6}$

The authors compared these results to earlier values developed by European agencies in the earlier 1990s, with the overall blade failure rate declining three times. It is expected that with the maturity of the industry blade failures will continue to decrease.

Documented blade failures and distances were also reported in the handbook. The maximum distance reported for an entire blade was 150 m, for a blade fragment the maximum distance reported was 500 m.

### 3.4. Rotor Fragment Analyses

This section discusses the estimates of rotor fragment risk as determined by six researchers. The impetus behind these investigations was to study the hazard potential of the rotor failure. While rotor failures can occur with the machine operating or stationary, these studies were limited to the operating case.

#### 3.4.1. Background of Rotor Fragment Models

##### **Parked Turbines**

Wind turbines are parked if the wind speed is out of the operating range, or if there is fault detected while the wind speed is within the operating limits. The typical high wind shutdown for a wind turbine is 25 meters/second, m/s. The turbine is usually designed to withstand a peak gust outlined by the International Electrotechnical Commission (IEC). Peak gusts for various wind classes are shown in Table 3. The peak gust is defined as a three-second average gust that has a fifty percent probability of occurring in fifty years, more succinctly known as “50-year wind.” The IEC wind classes are also distinguished by the annual average wind speed. All wind speeds are designated at hub height.

**Table 3. IEC peak gusts**

IEC Class	I	II	III
50-year wind	70 m/s	59.5 m/s	52.5 m/s
Annual Average	10 m/s	8.5 m/s	7.5 m/s

If a rotor has failed in a parked condition, there is no initial velocity of any fragment coming off. Any movement away from the turbine is governed by gravity and the aerodynamic force on the fragment. None of the analyses studied the failure of the parked turbine, and it is assumed that failure during operation will result in a higher probability of the blade or the blade fragment flying farther.

##### **Ballistics Models**

Analysis of rotor failure uses methods of classical dynamics in order to describe the problem. Figure 4 is a representation of a rotor failure. If there is a rotor failure, either a fragment or the entire blade, the motion of the fragment is governed by specific forces. If the failure has taken place while the turbine is operating, the fragment has an initial velocity due to rotation, while in flight the motion is constrained by gravity and aerodynamic forces. The initial velocity of the rotor fragment is a function of the tip velocity, determined by Equation 1:

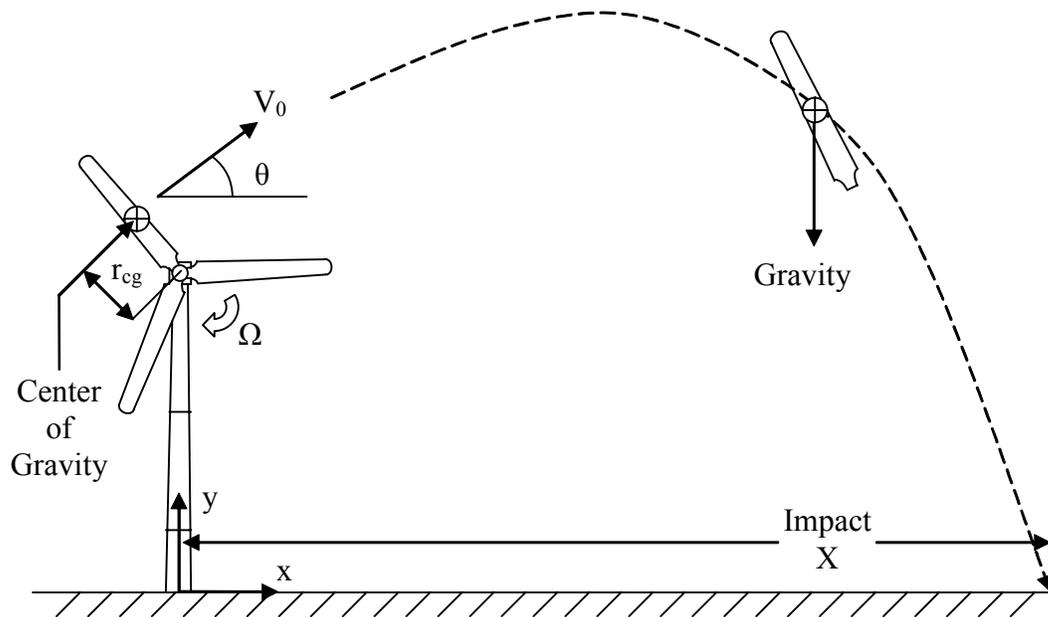
$$\text{Equation 1} \quad V_{tip} = \Omega R$$

where:

$\Omega =$  Rotor rotational speed, and

$R =$  Rotor radius

Normal operating tip speeds of the turbines studied in the literature varied from 40 m/s to 100 m/s. Modern wind turbines fall within this range. The tip speed is chosen to meet the performance requirements for the turbine and also to minimize acoustic emissions. The lower the tip speed, the lower the loads and noise from the blades for a given blade design. This can be compared to the low/high switch setting for a fan.



**Figure 4. Rotor fragment schematic**

If there is a failure of the rotor and a fragment is released, the initial velocity at separation is given by Equation 2:

$$\text{Equation 2} \quad V_0 = \Omega r_{cg}$$

where:

$V_0 =$  Initial velocity of fragment at center of gravity

$r_{cg} =$  Radial position of the fragment center of gravity

At the time of separation, the blade or fragment has the same angular velocity (or spin) as the rotor.

A rudimentary model of ballistics is the path of a fragment in a vacuum. The only force acting on the fragment is gravity. This model is found in most elementary dynamics

textbooks, such as Schaum's (Nelson, Best et al. 1998). The total ground range achieved by the fragment, with release height and impact height equal, is given by Equation 3.

$$\text{Equation 3} \quad X = \frac{V_0^2}{g} \sin 2\theta$$

where:

$X$  = Horizontal total ground range of a fragment in a vacuum

$g$  = Gravitational acceleration

$\theta$  = Release angle between the velocity vector and horizontal

The release angle is directly related to the blade azimuth, which is the position of the rotor at a particular time.

In a vacuum the aerodynamic forces are not modeled, the fragment is not affected by the ambient winds. The maximum range in a vacuum is achieved when the release angle is 45°. With this value of the release angle, Equation 3 becomes Equation 4.

$$\text{Equation 4} \quad X_{\max} = \frac{V_0^2}{g}$$

where:

$X_{\max}$  = Maximum horizontal range of a rotor fragment in a vacuum

The values of range from this simple model are not realistic because the atmosphere is not a vacuum. However, this simple model shows the importance of the release velocity because it is a squared term. For example, a 10% increase in release velocity increases the maximum range by 21%. This model also shows the dependence on the release angle. In any probability study, this would be a random parameter, because it is assumed that a rotor failure would not be dependent on the azimuthal angle.

Other models increase on the complexity of the vacuum model. The most common approach is to assume that the aerodynamic force is proportional to the square of the instantaneous velocity. The aerodynamic force is separated into lift and drag, and the constants of proportionality are called coefficients of lift and drag ( $C_L$  and  $C_D$ ). Both the crosswind and downwind distances are determined. The solutions for the fragment range from these models (so-called two-degrees-of-freedom or 2 DOF models) cannot be solved directly and require numerical methods.

The next level of complexity assumes that  $C_L$  and  $C_D$  are dependent on the orientation of the fragment, and the fragment is allowed to rotate and translate (3 DOF or 6 DOF models).

### **Rotor Overspeed**

One particularly hazardous failure scenario is turbine overspeed. The increased velocity in overspeed will over stress the rotor blade, and, in the event of a failure, increase the range of the fragment. The rotor is usually designed with a safety factor of 1.5. If the rotor loads are approximately proportional to the rotor speed (Eggers, Holley et al. 2001), the rotor could possibly fail at 150% of nominal rotor speed. To prevent this possibility, most wind turbines are equipped with redundant safety systems to shutdown the rotor. A turbine with industry certification (e.g. Germanischer Lloyd 1993), must have a safety system completely independent of the control system. The safety system must also have two mutually independent braking systems. Usually the blades pitch to release the aerodynamic torque while a brake is applied to the shaft. In the event of a failure in one system, the other system must be able to hold the rotor speed below maximum. An emergency shutdown is typically designed to occur if the rotor speed exceeds 110% of nominal. Even with redundant safety systems, rotor overspeed still occurs in industry, sometimes by human error when the safety systems have been defeated during maintenance.

### **Impact Probabilities**

The analyses next turn to the probability that a fragment will land on a certain target or in a particular area in the range of the turbine assuming a rotor failure. The studies follow various approaches to determine this probability; this will be discussed below. The probability of impact is then multiplied by the probability of rotor failure, discussed in the previous section. The final result is the probability that a target fixed at a certain range from the turbine will be hit in one year. If targets are not fixed, such as cars on a roadway, then the probability must be multiplied again by the probability that the target will be in position. Mobile targets are not discussed in the analyses.

A simplified impact probability can be derived from Equation 3. Since this relationship is only valid for a ground release, only release angles of 0 to 180° (see Figure 4) result in movement away from the release point. Release angles of 180 to 360° result in impact at the base. The random release angle is assumed to have uniform distribution from 0° to 360°. Using methods of probability, the probability that a fragment will fall within an annulus that is less than the maximum range is given by Equation 5.

$$\text{Equation 5} \quad P\{X_1 \leq X \leq X_2 \leq X_{\max}\} = \frac{2}{\pi} \left[ \arcsin \frac{X_2}{X_{\max}} - \arcsin \frac{X_1}{X_{\max}} \right]$$

where:

$X_1$  = inner radius of annulus.

$X_2$  = outer radius of annulus.

This relationship is plotted in Figure 5 for a normalized annular width of 0.05. Note that the relatively high probability of the fragment landing directly under the tower is not

shown. The nature of the equation results in an increasing probability of impact in the outermost annuli, due to a wide range of release angles that provide nearly the maximum range. However, the annular area increases with increasing radius.

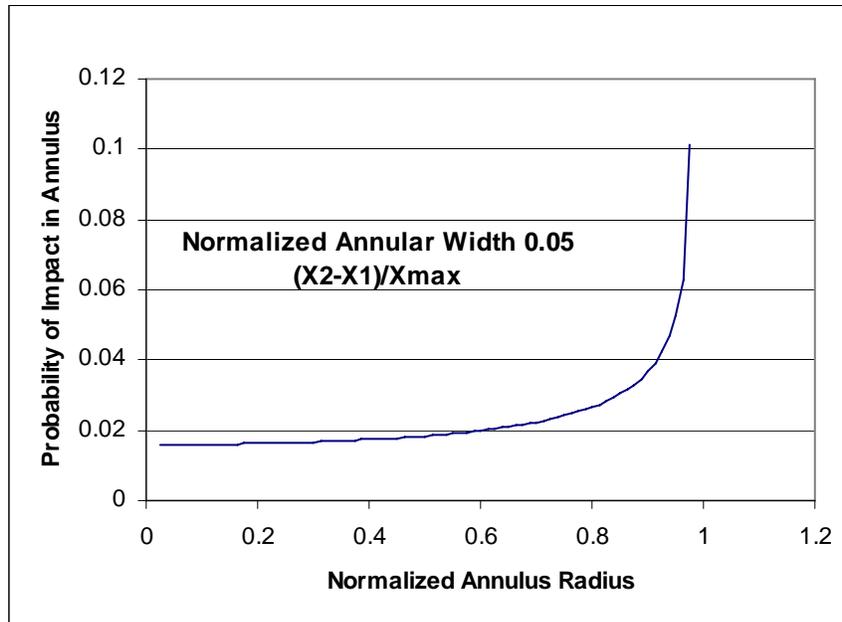


Figure 5. Probability of impact within an annular region

We next assume that the target is an annular sector, as in Figure 6.

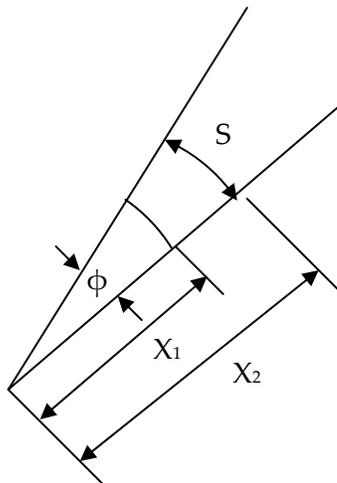


Figure 6. Target annular sector

In order to make the sector size roughly equal throughout the ballistic range, we set the outer arc length (S) equal to the annular width, given by Equation 6:

$$\text{Equation 6} \quad S \equiv X_2 - X_1$$

The arc length is also given by

$$\text{Equation 7} \quad S = X_2 \times \varphi$$

where:

$$\varphi = \text{Sector angle in radians (assumed to be small)}$$

Equating Equation 6 and Equation 7 and solving for the sector angle we obtain:

$$\text{Equation 8} \quad \varphi = \frac{X_2 - X_1}{X_2}$$

The probability of impact in this annular sector, assuming equal probability in all directions, is given by:

$$\text{Equation 9} \quad P\{X_1, X_2, \varphi\} = \frac{\varphi}{\pi^2} \left[ \arcsin \frac{X_2}{X_{\max}} - \arcsin \frac{X_1}{X_{\max}} \right]$$

This relationship is plotted in Figure 7. This simplified model shows a peak in probability near the tower base, and then a relatively constant probability until the probability rises again near the maximum range. This behavior is similar to more complex models incorporating aerodynamics. The peak at maximum range places a constraint on the overall hazard and acceptable setback distances.

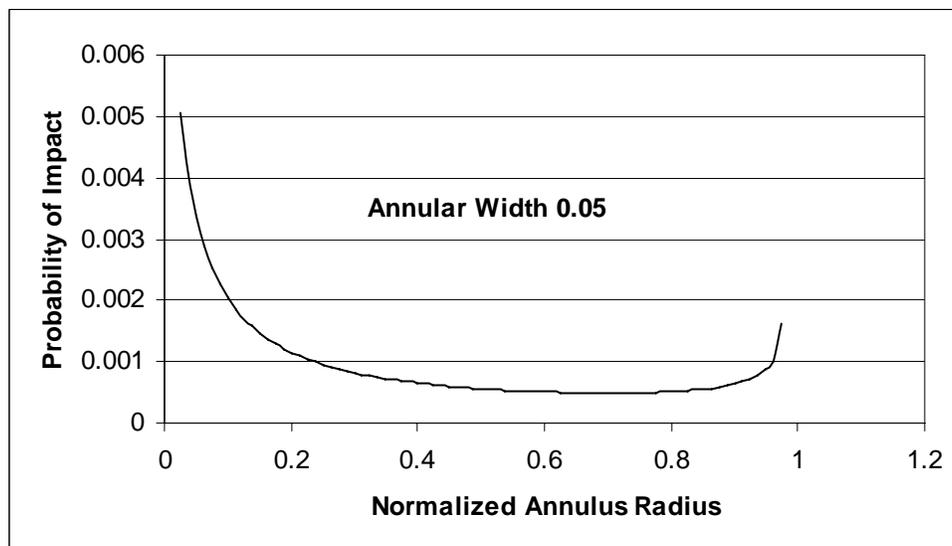


Figure 7. Probability of impact within annular sector

## **Multiple Turbines**

If there is more than one turbine in the area, such as in a wind plant, then the individual probabilities must be added for a particular area. This is mentioned briefly in Macqueen (1983). The probabilities add according to the Law of Total Probability; for two turbines this is represented in Equation 10.

$$\text{Equation 10} \quad P(A + B) = P(A) + P(B) - P(A, B)$$

where:

$$P(A + B) = \text{Probability of A or B or both occurring}$$

$$P(A) = \text{Probability of A occurring}$$

$$P(B) = \text{Probability of B occurring.}$$

$$P(A, B) = \text{Probability of both A and B occurring (Equation 11)}$$

$$\text{Equation 11} \quad P(A, B) = P(A)P(B / A) = P(B)P(A / B)$$

where:

$$P(B / A) = \text{Conditional probability B occurring given A has occurred}$$

$$P(A / B) = \text{Conditional probability of A occurring given B has occurred}$$

If the events are independent, which would be the case in a random failure, the conditional probabilities are from Equation 12 and Equation 13.

$$\text{Equation 12} \quad P(B / A) = P(B)$$

$$\text{Equation 13} \quad P(A / B) = P(A)$$

The overall probabilities become Equation 14.

$$\text{Equation 14} \quad P(A + B) = P(A) + P(B) - P(A)P(B)$$

As an example, consider a region that has a  $10^{-4}$  probability of impact from a Turbine "A" and a  $10^{-5}$  probability of impact from Turbine "B". From Equation 14, the overall probability of impact is:

$$P(A + B) = 10^{-4} + 10^{-5} - (10^{-4} \times 10^{-5})$$

$$P(A + B) = 1.1 \times 10^{-4}$$

These formulae can be expanded for multiple turbines.

### **Overall Probability**

The overall probability can then be compared to other risks. De Vries (1989) mentions a government policy in the Netherlands of one-in-a-million ( $10^{-6}$ ) per year risk level for new industrial activities. This is on the same order of present-day industry quality programs, such as "Six-Sigma," with a failure rate objective of three-in-a-million. Previously we discussed rotor failure probabilities on the order of one-in-a-thousand ( $10^{-3}$ ) to one-in-a-hundred ( $10^{-2}$ ). If we assume a conservative value of one-in-a-hundred ( $10^{-2}$ ), this results in a required probability of impact of less than one-in-ten-thousand ( $10^{-4}$ ) per year.

#### **3.4.2. Rotor Fragment Analyses in the Literature**

##### **Eggwertz, Sweden 1981**

This is the first documentation of a rotor fragment analysis, and is a comprehensive report on turbine structural safety for the Swedish industry. At the time, megawatt-size turbines were being considered for power production in Sweden. The analysis referenced previous work in Sweden on the possibility of fragment gliding due to spin; however the extension of the fragment flight was considered negligible. For the examination of risk areas, the drag coefficient in the analysis was fixed at 0.5 for lateral and downwind directions, and the lift coefficient was assumed to be zero.

For the probability analysis the blade and azimuth locations were divided into equal spanwise sections and equal weighting was applied to failure at these sections. This allowed for a semi-random probability of failure of the blade at a particular section and at a particular azimuth. A total of 144 fragment releases were modeled. A discussion was made of the probability of rotor failure, mentioned in the Rotor Failure section, but no criteria were applied in the final analysis.

The discussion of the physics and probability of impact is very detailed. The risk area included considerations of sliding and rotation of the rotor fragment. The fragment was assumed to translate on the ground and come to a complete stop due to friction. The area surrounding the turbine was divided into 10-m rings and the fragment impact area within the ring was divided by the total ring area. The probability calculated assumes equal probability of launch for all wind directions. The result was the risk level that a target within a ring will be hit.

The overall analysis was conducted for a 39 m radius machine at an 80 m hub height operating at 25 rpm in a 7 m/s wind speed. This was considered to be the most likely operating condition. Assuming that a failure had occurred, the probability was high at the tower base and then relatively even at  $10^{-3}$  until 200 m. The analysis showed the probability of impact from any fragment dropped off dramatically (below  $10^{-5}$ ) at 220 m. This throw distance is 1.8 times the overall turbine height. The throw distance for a probability of  $10^{-4}$  is only slightly less than this value. The dramatic drop off in the probability at 220 m was used as a basis for the safety area around the turbine; however, the calculations were made at nominal operating conditions and at a single wind speed. Failures in an overspeed conditions would increase this area.

### ***Montgomerie, Sweden 1982***

Montgomerie (Montgomerie 1982) expanded on Eggwertz's work by modeling the fragment with a full six-degrees of freedom. The aerodynamic model is not explained but is referenced from an unpublished thesis in Sweden. Similar work would later be developed by Sørensen (1984a).

Montgomerie presents results for an example turbine similar to Eggwertz's. The break at the rotor and the azimuth at break are treated with equal probability. However, the new model includes a wind speed and wind direction distribution from the wind turbine site. The normally circular hazard contour is only made slightly oval with the wind direction distribution. The maximum throw distance for the example exceeds 1600 m and the distance for  $10^{-4}$  probability is 1500 m. These values are much greater than Eggwertz's results; however, there is no explanation for the discrepancy between them. The results are also relatively higher than results presented by other researchers.

### ***Macqueen, United Kingdom 1983***

This work was conducted in the United Kingdom for the Central Electricity Generating Board. As in Sweden, the United Kingdom was considering generating electricity with megawatt-size wind turbines. Macqueen starts by bounding the problem with an analysis of the maximum launch velocity of a rotor fragment being limited by the approach of the speed of sound. An estimate of the maximum velocity is 310 m/s in an extreme overspeed condition for a typical turbine. The fragment distance would not exceed 10 km using classical ballistics results with no aerodynamic drag. It is unreasonable to expect setback criteria of this distance; the turbine rotor would probably fail at a much lower velocity, plus the aerodynamic drag acting on the fragment would greatly reduce the distance. However this provides an upper extreme limit.

The analysis followed the same lines as Eggwertz with analysis of gliding and tumbling and classical ballistics with average lift and drag coefficients. The tumbling analysis was to determine the conditions for stable, gliding flight of a fragment. Macqueen reasoned that the flight time of a fragment was several times longer than one tumbling period and therefore stable flight could not be expected. However gliding was considered as a rare case if the fragment did not leave with sufficient rotational energy. For the tumbling case, Macqueen reasoned a  $C_L$  of 0.0 and a  $C_D$  of 1.0. For gliding, lift was chosen as  $C_L=0.8$  and  $C_D=0.4$ . Macqueen estimated the probability of gliding occurring in a potential failure at  $10^{-2}$  to  $10^{-3}$ .

Macqueen also included a discussion of a three-dimensional model of fragment flight, and concluded that the model did not show the fragment achieving a stable gliding condition. Macqueen concludes that the effect of lift in the three-dimensional case increases the range of flight by no more than 10%.

A series of runs at equally spaced azimuthal positions were used to develop the probability distributions. The possibility of sliding after impact was not addressed in the current work. He then separated the analysis into two failure events, one at a 10%

overspeed at average winds, the other at the maximum possible release velocity with an extreme gust. The turbine studied was of similar geometry to the MOD-2, with 91 m diameter rotor and 61 m hub height.

The probability of impact is weighted by area (per square meter), and assumes equal distributions in all directions. Probability distributions showed peaks near the tower and at the maximum range, similar to the results of the simplified model in Figure 7. The probability of impact was then a function of the target and fragment size. Macqueen reasoned that the rotor fragments would be large compared to target, making the probability independent of target size; however this would not be the case with a busy roadway, with many targets over a large area.

For overall probabilities Macqueen used the Eggwertz probability of  $10^{-5}$  for rotor failures. Macqueen also compared the probabilities to a statistic of risk of death by lightning strike in the United Kingdom at  $10^{-7}$  per year. For the turbine studied, a large 2.5 MW unit, the risk of being hit by a rotor fragment within 210 m (approximately two times overall height) is equivalent to being struck by lightning. However, these results were based on the rotor failure probability of  $10^{-5}$  and the assumption of a target size less than the overall fragment area.

#### ***Sørensen, Denmark 1984***

This investigation was part of the wind power program of the Ministry of Energy and the Electric Utilities in Denmark. The conference paper (Sørensen 1984b) was a summary of the full report in Danish. Detailed sensitivity studies are found in the Wind Engineering paper (Sørensen 1984a). The analysis is unique in that the aerodynamics of the fragment under ballistic motion was fully modeled. Sørensen used synthesized data from a NACA 0012 wing to simulate the fragment under various alignments. The blade fragment was broken into segments and the aerodynamic forces were determined independent of each other. The total force was then a summation of the individual forces. This approach is similar to current state-of-the-art modeling of wind turbine rotors in the industry. Three turbines of increasing size were studied.

The modeling showed that the fragment tumbling motion decayed as it reached the maximum height with the heavy end directed down as the fragment fell back to earth. This behavior was also described by Eggwertz in scaled model studies. The model behavior places into question the pure tumbling and constant aerodynamic coefficients of the other models. Comparison with these models showed that the average drag coefficient for the lateral throw would have to be varied from 0.15 to 0.4 to achieve similar results to the full aerodynamic model. These coefficients are lower than what has been considered by the other researchers. For the downwind range, the constant coefficient models predicted a much lower distance. Therefore, constant coefficient models would tend to predict shorter overall throw distances compared to Sørensen's method.

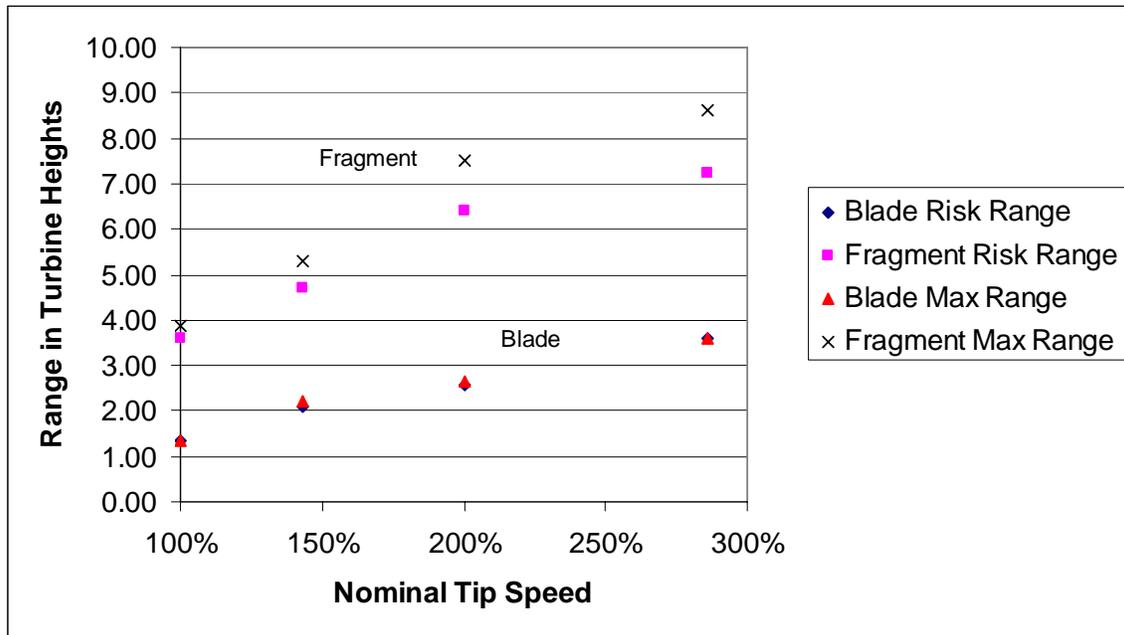
The *Wind Engineering* paper went through several sensitivity studies of the modeling parameters. A summary of these studies is presented in Table 4.

**Table 4. Sensitivity studies by Sørensen in *Wind Engineering* paper**

<b>Subject</b>	<b>Description</b>	<b>Results</b>
<b>Airfoil Data</b>	Analysis conducted on four airfoil data sets	7% spread in maximum range
<b>Aerodynamic Unsteadiness</b>	Dynamic aerodynamic loads modeled	12% reduction in maximum range with unsteady model
<b>Autorotation</b>	Model tendency of fragment to glide like helicopter rotor	Substantial reduction in range
<b>Center of Gravity Location</b>	Vary chordwise center of gravity position on fragment	Negligible effect for typical 25-35% chord line placement
<b>Blade Pitch Angle</b>	Blade pitch angle at moment of release	Large influence; pitch of maximum thrust had maximum range
<b>Wind Velocity</b>	Ambient wind velocity at moment of release	Large influence, partially due to dependence on pitch angle effect

The impact probabilities reported in the conference paper (Sørensen 1984b) assumed the target as a one-meter sphere. Sliding of the wreckage was assumed, with 25 meters of slide assumed for a throw greater than 75 m range. As stated before in the Macqueen (1983) discussion, these probabilities would have to be adjusted for targets larger than the blade fragment, such as a busy roadway, or a dwelling. The probability analysis followed the same approach as Eggwertz (1981) by dividing the region around the turbine into ring segments. Uniform wind direction was assumed.

Probabilities were only presented for the Project “K” turbine for a full 30-m blade throw and 10-m blade fragment throw. This turbine is of 1.5 to 2.0 MW size with a 60 m hub height. Release angle and wind speed were varied and multiple throws were calculated. The probabilities were presented as a function of tip speed. Results are shown in Figure 8, comparing the range with  $10^{-4}$  probability (the “risk” range) to the maximum range.



**Figure 8. Throw distances in Sørensen conference paper with  $1 \times 10^{-4}$  probability risk range**

The maximum ranges do not increase exponentially as would be predicted for a vacuum in Equation 4. This is the result of including the aerodynamic forces. Also, there is negligible difference for the full blade maximum range and range with  $10^{-4}$  probability. This is not true for the fragment.

**Turner, United Kingdom 1986 and 1989**

Turner’s (1986) work was a further expansion of MacQueen’s work. He starts by developing a model of the probability similar to that in Section 0. He uses this model to form conclusions of the overall statistics of the more advanced problem. He used a Monte Carlo method to run simulations of fragment throws with the simple model, and then performed a chi-squared test with the exact solution of the simple problem to show the validity of the Monte Carlo method. He also developed a method to determine confidence levels after a certain number of throws so that an appropriate number of throws can be determined.

Turner assumed a geometric distribution for the probability of the rotor break point. It was assumed that inboard portions of the blade were twice as likely to break as outboard portions. Equal distribution was assumed for the azimuth position of break. For impact, he developed a bouncing model that he considered conservative based on data from artillery tests. He used a cutoff angle of  $20^\circ$  above which bouncing was not permitted. He also used Eggwertz model for sliding after impact.

Turner later expanded on his work to include a six-degree of freedom model of the fragment (Turner 1989). His model dynamics were similar to (Montgomerie 1982). The aerodynamic model used two-dimensional airfoil data with no adjustment for off-axis

flow. A small drag value was added for spanwise flow. He presented results of Monte-Carlo simulations for several model conditions.

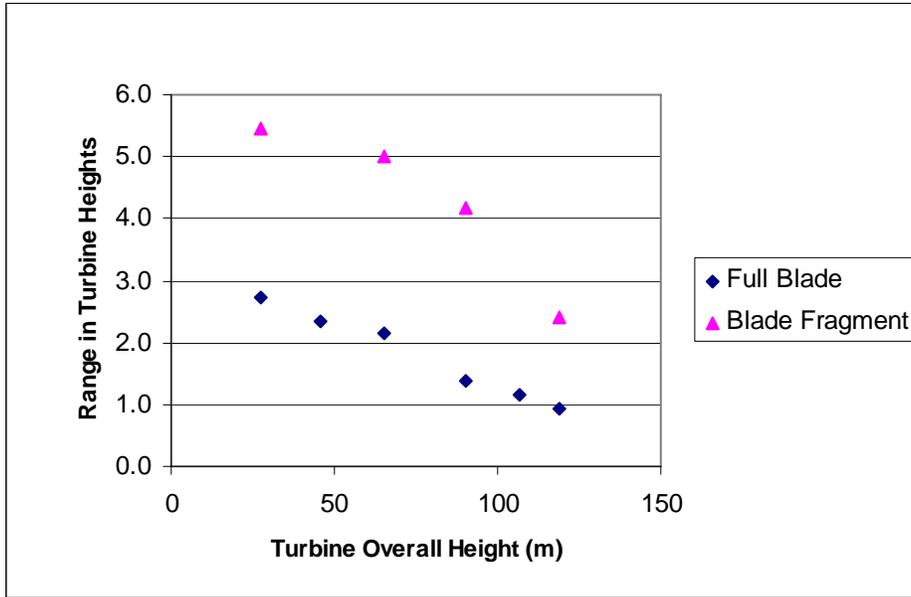
### ***Eggers, United States 2001***

This is the most recent analysis (Eggers, Holley et al. 2001) generated for the National Wind Technology Center in Colorado. The analysis used classical ballistic theory and assumed constant values of aerodynamic force coefficients. A discussion and analysis is made of the possibility of gliding flight assuming the blade achieves a stable gliding angle; it is assumed negligible. The low probability of this is reasoned due to the complex geometry of the blades, with varying chord, airfoil section, and twist. The mean values of drag ( $C_D = 0.5$ ) and normal force coefficients are considered constant during flight. Half and full-blade fragments are analyzed.

An example turbine was studied with a 15.2 m rotor radius operating at 50 rpm in 11.2 to 22.4 m/s winds. A probability distribution, assuming equal weighting for all directions, was determined analytically and solved numerically. This method was unique in that several trials of throws were not necessary to obtain the distributions. Also assumed was that the failure was the result of an overspeed, and that the range of the overspeed failure was a Gaussian distribution between 1.25 and 1.75 times the nominal speed. Eggers, like Macqueen (1983), confirms peaks in the probability distribution near the tower and at maximum range. Two tower heights were also studied, showing higher probability at the tower base for the shorter tower. Probability values cannot be determined from the paper due to the limited resolution of figures.

### ***3.4.3. Comparisons of Rotor Fragment Analyses***

Studies of example turbines were performed in all the analyses discussed previously. A comparison is shown below in Figure 9. The maximum attainable lateral throw distance, normalized by overall turbine height, for a failure at nominal operating conditions is shown for the various analyses. The results show the drop in the normalized maximum throw distance with increasing turbine size.



**Figure 9. Comparison of rotor fragment analyses for maximum range at nominal operating conditions**

## 4.0 Conclusions and Recommendations

### 4.1. Conclusions

This study was performed on setbacks for permitting of wind energy. Counties with past and future development of wind energy have setbacks based on overall turbine height. A simple example was presented showing the negative economic impact of setbacks based on size for modern turbines. The application and size of the setbacks varied widely across the counties. However, a common setback is three-times the overall turbine height from a property line.

Most setbacks were established early in the development of the wind industry and were outcomes of ad hoc groups of government and industry. Other counties followed suit based on the example of the early developments. There is some evidence for Riverside County that the “three-times” rule may have been an outcome of expected spacing to reduce waked operation losses. There is no evidence that setbacks were based on formal analysis of the rotor fragment risk.

CWEC also studied the probability of wind turbine rotor failure. Reporting of wind turbine failures are scarce in the literature, but available data from Alameda County and Europe show rotor failures from approximately one-in-one-hundred ( $10^{-2}$ ) to one-in-one-thousand ( $10^{-3}$ ) per turbine per year. The most comprehensive study from the Netherlands reported failures for European turbines of approximately one-in-one thousand ( $10^{-3}$ ) per turbine per year.

Six studies examined modeling of the rotor fragment risk in detail. Several researchers analyzed but discounted the possibility of gliding flight, and instead used simplified aerodynamic models. Sørensen (1984a) used a three dimensional analysis of the rotor fragment flight and showed the limitations of the simplified models. The literature does not offer any guidance for applying setback distances that would be useful for wind energy planning.

Two observations can be made from a comparison of the analyses with failure at the nominal operating condition. The first is that as the overall turbine height increases, the range normalized by overall height decreases. This is primarily because the maximum range is dependent on turbine tip speed. As discussed previously, the tip speed has remained nominally unchanged as turbine size has increased. The other conclusion is that blade fragments fly farther than full blades. This is because the initial velocity at failure tends to be higher for the fragment than the entire blade. This result indicates that setbacks based on overall turbine height may be reduced for larger turbines.

### 4.2. Recommendations

The setback literature reviewed in this report does not provide an analytical rationale for determining wind turbine setbacks. However, after reviewing the literature for analysis of the rotor fragment hazard, CWEC proposes the following items to develop guidelines for setbacks.

#### **4.2.1. Rotor Failure Rate and Operating Conditions at Failure**

The rotor failure probabilities presented by Rademakers and Braam in Appendix A represent the most comprehensive study. The values presented in Section 3.3.4 should be used for analysis of the overall hazard. These values are organized by rotor speed, which can be used to set the release velocity at failure. However, the wind conditions at failure are not known. Simulations can be performed at several wind speeds, and either the worst case could be used, or the results can be weighted by a standard wind speed distribution.

#### **Turbine Sizes**

A mixture of turbine sizes should be studied to determine if setbacks should be a standard distance or a function of the turbine size. Turbine sizes currently marketed are 660 kW to 5 MW. Smaller turbines should be studied for stand-alone applications and review of existing hazards.

#### **4.2.2. Position of Blade Break**

Since the position of the failure cannot be predicted with certainty, the approach of Eggwertz (1981) to divide the blade into sections should be used. In addition to randomizing the break position, turbines with blade components such as aerodynamic devices, blade dampers, and lightning protection should be studied as fragments.

#### **4.2.3. Aerodynamic Model**

The methods of Sørensen (1984a) should be applied for the aerodynamic model. This model was the most comprehensive and showed the limitations of constant aerodynamic coefficient models. The model is well documented and can be updated to modern programming languages. There was an effort to update this program to MATLAB® at the Technical University of Denmark (DTU); however the status of this work is unknown.

Further studies could be conducted to incorporate shear and turbulence into the model. With these effects included, the rotor fragment might exhibit constant lift coefficient and drag coefficient behavior which might warrant use of simpler models.

The model should be built as a tool that can be used by the industry for use on any turbine to study specific cases, such as permitting waivers.

#### **4.2.4. Impact Modeling**

The methods of (Turner 1986) and Eggwertz (1981), or Sørensen (1984a) should be used to model the physics at impact. The methods include bouncing at impact and the effects of rotation and translation after impact.

#### **4.2.5. Slope Effects**

Slope effects were not included in the reviewed analyses. Because of the common placement of turbines on ridgelines, as in the Altamont and the Tehachapi wind resource areas, modifications to the setback distance should be studied. Modifications should be stated in simple language, similar to the language in the Alameda ordinance.

#### **4.2.6. Validation Effort**

None of the analyses have been validated with actual failures. Validation with an actual failure can be made with the following information:

- Turbine tower height
- Rotor diameter
- Position of failure on rotor
- Azimuth of failure (would be very hard to obtain)
- Rotor speed
- Pitch of blades
- Geometric details of the fragment (planform, airfoils, weight, center of gravity, twist distribution)
- Wind speed, direction, and local air density
- Distance and bearing of blade or fragment from tower base

Another effort would be to deliberately cause a rotor failure and obtain the above information. This test could be conducted on a turbine at the end of its useful life in a clear field. Explosive bolts or a ring charge could be used to separate the blade or fragment from the turbine. The azimuth at break must be carefully determined.

## **5.0 Benefits to California**

Researchers should use the information as background for developing models of the rotor fragment hazard. California planning agencies should then use this new rotor fragment hazard information, together with the information in this report as a tool for modifying or establishing wind turbine setbacks.

A better understanding of the risks involved with wind energy will permit the development of appropriate methods to manage that risk, thereby increasing the acceptance of wind energy developments by local governments and the general public.

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## 7.0 Glossary

Specific terms and acronyms used throughout this paper are defined as follows:

<b>Acronym</b>	<b>Definition</b>
$C_D$	Coefficient of drag
$C_L$	Coefficient of lift
CWEC	California Wind Energy Collaborative
DOE	U.S. Department of Energy
DOF	degrees of freedom
DTU	Technical University of Denmark
EIR	Environmental Impact Report
IEC	International Electrotechnical Commission
kW	Kilowatt (1000 Watts)
m	Meters
m/s	Meters per second
MW	Megawatt (1,000,000 Watts)
NREL	National Renewable Energy Laboratory
RPM	Revolutions per minute
SERI	Solar Energy Research Institute (predecessor of NREL)
WECS	Wind Energy Conversion System



# **Attachment I**

## **ANALYSIS OF RISK-INVOLVED INCIDENTS OF WIND TURBINES**

Version 1.1, January 2005

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# 1. INTRODUCTION

As part of the project “Handboek Risicozonering Windturbines (Guide for Risk-Based Zoning of Wind Turbines),” research was conducted on incidents involving wind turbines that may pose a risk to their surroundings. This information is used to quantify the failure events, as well as for the development of a method, described in the Guide, to calculate the risks. These risks include blade failure, tower failure, or any other parts of the wind turbine falling off. In order to determine these risks, it is necessary to understand the possible failure events, and the frequency of these events. Validation of the calculation method is impossible by means of experimentation, but in order to gain sufficient trust in the method it is necessary to have information on what part of the blade has fallen off, its size, and the distance it traveled after separation from the turbine.

To determine the failure frequency of blades, towers, and other parts of a particular wind turbine, the ISET (Institut für Solare Energieversorgungstechnik) in Germany and the EMD (Energie- og Miljødata) in Denmark have provided information [1,2]. Both institutes have a database containing energy production, incident, and maintenance information for most of the wind turbines in Germany and Denmark, respectively. Incidents and occurrences of importance are selected based on the raw data that is extracted from the ISET and IMG databases, in order to obtain insight into possible failure events. This information is also used to determine the frequency of failure events per year, as well as to provide information about the uncertainties. In this appendix the extracted data from the ISET and EMD databases are combined and then applied to calculate failure frequencies.

A supplementary study was conducted based on the throw distance, dimensions of thrown parts, etc. Based on information from the internet, magazines, and detailed information in ISET and EMD reports, a summary of incidents and the related throw distances for different types of turbines was made. The results of this research are included in this appendix.

When reading this report and applying the information in it, it is important to keep in mind the following:

- The data, particularly the number of incidents, are never complete. Not all incidents are reported or known to the ISET, EMD, or ECN. To prevent this from leading to false results, the population of wind turbines for which statistics are calculated is specifically chosen so that all incidents involving these turbines are known.
- It is not always possible to determine the way an accident developed. Sometimes it is clearly reported that a blade (or two blades) has broken off and landed 100 m from the turbine. Sometimes it is only reported that a blade has been damaged and replaced, without any reports of pieces that may have broken off and been thrown from the

turbine. In cases where the extracted data were incomplete, a suitable conservative interpretation of the data was applied.

Based on the information, five separate categories have been determined that are of importance for the risk analysis.

1. Whole turbine blades or very large blade pieces breaking off and being thrown.
2. Brake tips and other blade pieces such as blade surface panels, composite material, bolts, etc. being thrown from the turbine.
3. Tower collapsing.
4. Large parts, such as the nacelle, the whole rotor, or other main components, falling down.
5. Small parts, such as the anemometer or bolts, falling down from the nacelle or the hub.

The reasons for this classification are as follows.

1. A blade that has broken off can be thrown relatively far and has a large mass. It can cause relatively heavy damage to another object.
2. A brake tip or a small part of a blade can be thrown very far. Because it has a small mass, the chance of doing damage to another object is smaller than that of an entire blade.
3. The collapse of a tower usually means great risk to anything in close proximity of the turbine. The entire turbine has an extremely large mass and can therefore cause heavy damage to anything close to the turbine.
4. Similarly to the tower collapse, the fall of a large component such as a nacelle can cause heavy damage to anything close to the turbine.
5. Small parts that fall down cannot cause heavy damage. The risk area for this situation is limited to just a few meters from the tower.

Each category requires a different approach to the risk analysis.

The shedding of ice is not listed here explicitly. The calculation of vulnerable distance and risks for ice can be based on those for category 2 “brake tips and small parts of blades.” The frequency of ice being thrown from a blade is very location dependent and therefore the importance of this phenomenon cannot be determined generally for a turbine. Furthermore, the AMvB [3] stipulates that wind turbines with ice on their blades are forbidden to start up.

In this report the following topics are addressed consecutively:

- Results of the analysis of the EMD database.
- Results of the analysis of the ISET database.
- Calculation of the frequency of failure for the categories listed above.
- Results of the analyses concerning the development of a calculation method for throw distances.
- A summary of the failure frequencies and a recommendation on the application of these values in risk analyses.

## 2. ANALYSIS OF DANISH FAILURE DATA

### 2.1 Introduction

Energie- og Miljødata (EMD) has a database that contains approximately 6000 turbines in Denmark. The energy production and failure data are registered for over half of these turbines. The owners of the turbines can voluntarily submit a monthly report to the Danish Association of Turbine Owners. This association performs an initial analysis of the information and then codes it. The data is then sent to EMD. EMD feeds the information into their database. In total, EMD has selected and reported 210 risk involved incidents [1].

The main goal of the analysis of the EMD-provided information is the selection of incidents and the calculation of failure frequencies for the five categories (blades, tips, tower, nacelle and rotor, or small parts). In determining the number of relevant incidents and determining the size of the population of turbines, attention is paid to the following.

- The size of the total population of turbines is not always known. Not all turbine owners submit monthly information. This can mean that there were no incidents, or that the incidents were not reported. In particular, energy production numbers of turbines that belong to electric utilities are submitted monthly, but incidents are seldom or never submitted. Of the remaining turbines, incident reports are regularly submitted with the energy production numbers. EMD has followed a conservative approach, and only included those turbines for which incidents are regularly reported. Most turbines belonging to electric utilities are therefore left out of the analyses. It is very probable that most turbines larger than 1 MW belong to the electric utilities. This is exactly the type of turbine that is most important for future risk analyses.
- Blade fracture is relevant to all turbines; a flyaway tip is only relevant to stall regulated turbines with blade tips. Therefore, the size of the total population can be different for each analysis.
- Most incidents are poorly documented, and the actual number of risk-involved incidents cannot be determined for certain. EMD uses codes to indicate which component failed, the reason for failure, and whether parts were thrown from the turbine. From the codes it is difficult to determine the size of the thrown object, the distance thrown, and the order of events. In some cases this information is included in the comments. Between 1993 and 2000 the code was expanded. Between 1984 and 1992, the code was severely restricted. It was seldom even noted whether a compromised turbine had done damage to the surrounding area. This made it possible for a turbine that had a complete failure and lost many parts (see Fig. 2.1) to be reported exactly like a turbine that had a complete failure and posed no risk to the surrounding area (see Fig. 2.2).



**Fig. 2.1: Two examples of incidents that pose possible danger to the surrounding area.**



**Fig. 2.2: Two examples of turbines that failed, but caused no danger to their surroundings.**

## 2.2 Turbine Population

The turbine population from 1984 through 2000, as provided by EMD, is separated into the different types. The results are presented in Fig. 2.3. At the end of the year 2000 the total turbine population reached about 2900 turbines. The total number of operating years reached almost 30,000. By far the most turbines are stall-regulated turbines.

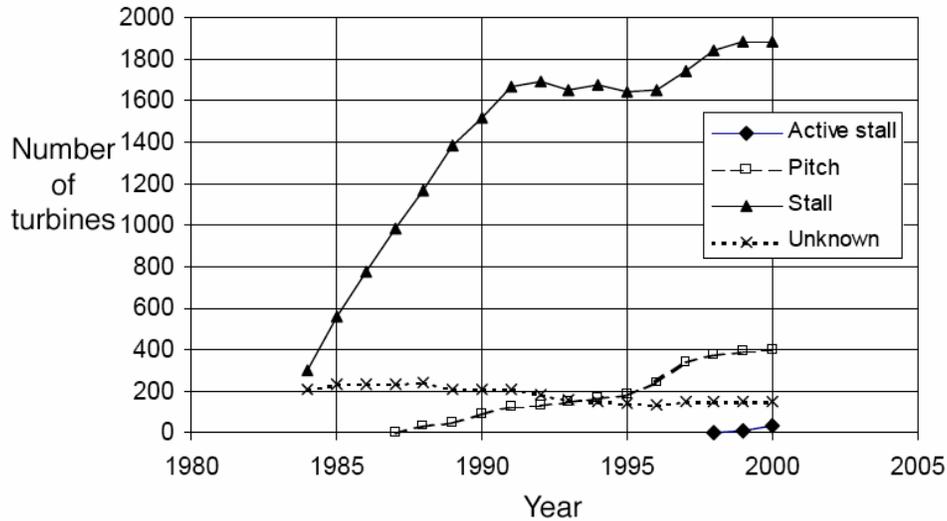


Fig. 2.3: Number of wind turbines in the EMD database, separated by type.

When the turbines are separated into groups based on rated output, the distribution as shown in Table 2.1 is established.

Table 2.1: Number of operating years, separated into groups based on rated output

Rated Output [kW]	Operating Years	Percentage
0 - 50	3229	11.0%
51 - 300	24368	82.8%
301 - 750	1769	6.0%
751 - 1300	47	0.2%
1301 -	0	0.0%
Total	29413	100.0%

## 2.3 Failures and Incidents

As is briefly discussed in paragraph 2.1, not all incidents are reported with enough detail to make unambiguous conclusions. EMD has created the following four categories to indicate how dangerous an incident is:

3. Definitely dangerous, unambiguously reported
2. May be dangerous, but not for certain
1. Not dangerous, unambiguously reported
0. Necessary information missing

In many cases it appeared difficult to indicate exactly whether a turbine had indeed lost parts as in Fig. 2.1, or was just heavily damaged as in Fig. 2.2. The final results from the selection of risk involved incidents are given in Table 2.2. The total can be seen in Table 2.3. This table includes the total number of operating years for each type. This number is obtained by summing the number of turbines in operation per year over all the years.

**Table 2.2: Number of risk involved incidents per year for each regulation type. For each type, number of turbines in operation at that point is given per year.**

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Active stall															3	10	30
Blades																	
Tips																	
Turbine, nacelle, large parts																	
Small parts																	1
Pitch				4	35	53	88	126	134	153	170	183	239	339	373	389	399
Blades																	
Tips																	
Turbine, nacelle, large parts																	
Small parts																	1
Stall	300	557	772	984	1167	1386	1517	1664	1689	1648	1675	1642	1651	1743	1839	1885	1887
Blades							2	3		2	1	1		1	1		1
Tips									1							1	1
Turbine, nacelle, large parts										1							1
Small parts			1								5	2	4	1	2	3	2
Unknown	210	230	234	237	245	209	208	207	181	155	152	144	136	150	153	154	150
Blades			1		1												
Tips																	
Turbine, nacelle, large parts				1			1		2								
Small parts																	
Total # turbines	510	787	1006	1225	1447	1648	1813	1997	2004	1956	1997	1969	2026	2232	2368	2438	2466
Total # failures with dropped parts	0	0	2	1	1	0	3	3	3	3	6	3	4	2	4	6	4

**Table 2.3: Total of all risk involved incidents, total for all operating years, and the number of operating years for each type of turbine.**

	<b>1984-1992</b>	<b>1993-2000</b>	<b>Total</b>
Active Stall	<b>0</b>	<b>43</b>	<b>43</b>
Blades			
Tips			
Whole Turbine			
Small Parts		1	1
Pitch	<b>440</b>	<b>2245</b>	<b>2685</b>
Blades			
Tips			
Whole Turbine			
Small Parts		1	1
Stall	<b>10036</b>	<b>13970</b>	<b>24006</b>
Blades	5	7	12
Tips	1	2	3
Whole Turbine	1	2	3
Small Parts		19	19
Unknown	<b>1961</b>	<b>1194</b>	<b>3155</b>
Blades	2		2
Tips			
Whole Turbine	4		4
Small Parts			
Turbine Years	<b>12437</b>	<b>17452</b>	<b>29889</b>
Total Incidents	<b>13</b>	<b>32</b>	<b>45</b>
Total Suspected Incidents	55	51	106

In the time period between the years 1993 and 2000, in total there were 11 “category 3 incidents” reported, and 66 “category 2 incidents.” Based on the information provided by EMD, and after reading the commentary, there appeared to be 51 suspicious incidents; of the 77 total incidents, 26 could be eliminated. Of the 51 suspicious incidents, 32 were proven risky and were included in the analysis. Between 1984 and 1992 there were 55 suspicious incidents, and 13 ended up being included in the analysis.

From the detailed analysis of the incidents, it seems that some cases involved multiple parts breaking off and being thrown. With blades, for example, it is possible for one, two, or three blades to be thrown. In the seven incidents involving blade throw between 1993 and 2000, a total of ten blades were thrown. There were no incidents reported that involved more than one object when it came to the tips and small parts. Clearly when the incident involved the tower or nacelle, only one object can be affected. That is why there is a multiplication factor of 10/7 used in calculating risk for the blades. The total number of incidents and the corresponding population of turbines are tabulated in Table 2.4.

In EMD’s report, only failures of the whole turbine were reported; no distinction was made between the categories “nacelle and rotor” and tower failures. When the part listed was the “turbine,” it was not immediately clear whether it was the tower or the nacelle that was affected. Later analyses of the raw data, according to tables 2.2 and 2.3, showed that at least 2, maybe even 3, of the 7 incidents involved the whole tower collapsing. That is why in table 2.4 there are half incidents.

**Table 2.4: Overview of incidents in the total wind turbine population**

Part	84-92	93-00	84-00	Factor	Total	Turbine Years	Notes
Blades	7	7	14	1.4	20	29889	Total number of turbines
Tips	1	2	3	1.0	3	24006	Total number of stall turbines
Nacelle	3.5	1	4.5	1.0	4.5	29889	Total number of turbines
Tower	1.5	1	2.5	1.0	2.5	29889	Total number of turbines
Small Parts		21	21	1.0	21	17452	Total number of turbines between 1993 and 2000
<b>TOTAL</b>	<b>13</b>	<b>32</b>	<b>45</b>				

As can be deduced from the previous paragraphs, determining the number of incidents within the scope of the entire turbine population is done with much uncertainty. The population used by EMD involves mostly three-bladed, stall regulated turbines, with a rated output of up to 750 kW. This population is made up of about 2900 turbines. Future turbines for which the risk analysis is being done will most likely be pitch regulated turbines with an output greater than 1 MW. It is these types of turbines for which EMD has little information. It is not clear if there were indeed no incidents, or if they merely were not reported.

## 2.4 Trends

Simultaneously the correlation between the age of a turbine and its frequency of failure was researched. For this the 32 critical incidents between 1993 and 2000 were divided into four time periods (0-5 years, 5-10 years, etc.). The number of incidents in each time period is divided by the number of turbines that fall into that category. (Note that determining the population of turbines in each category could not be done with great accuracy. The number of turbines between 0 and 5 years old was determined by subtracting the number of turbines in operation in 1995 from the number of turbines in operation in 2000. It is unclear whether there were turbines taken out of operation or replaced). Most failures were caused by turbines between 5 and 10 years old.

The relationship between the rated-power category of the turbines and their failure frequency was also researched. The number of incidents in each rated-power category is divided by the number of years in operation for each category. No trend is found.

## 3. ANALYSIS OF GERMAN FAILURE DATA

### 3.1 Introduction

ISET has made an inventory of “critical losses” that have occurred in Germany over the past 10 years. ISET has defined a “critical loss” in the following way.

*A critical loss is a sudden and lasting change in a wind turbine that can potentially or definitely cause damage to the surrounding area. The cause of the change can be due to external sources (e.g. lightning and storm), or internal sources (fatigue).*

It is therefore not conclusive that the recorded cases did cause damage to the surrounding area. This inventory is in principle based on the WMEP database (Wissenschaftliches Meß- und Evaluierungsprogramm), which is managed by ISET. Additional information was obtained from technical publications and the internet.

Information from approximately 1500 turbines in Germany has been collected in a systematic manner in the WMEP database since 1989. The results of these 1500 turbines provide a representative overview for the approximately 10,000 total turbines that have been installed in Germany. The database contains over 48,000 entries. In order to facilitate analysis of the database, the above definition for a critical loss is used as a starting point.

Based on this definition, a number of search criteria have been devised for the database. The most important criteria used are:

1. The shutdown of a turbine has to be the result of a failure (preventive maintenance and other planned activities are thereby eliminated);
2. Eligible failure modes are:
  - Storm
  - Lightning
  - Defective component
  - Defective assembly or mounting
  - Other causes;
3. A repair or a replacement is required for one of the following main components:
  - Rotor hub

- Blade
- Nacelle
- Tower

Repairs or replacements of gear boxes or generators are not included, because a failure of these components rarely causes potential danger to the surrounding area.

The automatic search of the database with the aforementioned criteria resulted in 152 matches. These matches are subsequently scrutinized one at a time by ISET, resulting in a further reduction of the number of incidents. This finally resulted in 43 cases that could actually be reported as involving serious damage.

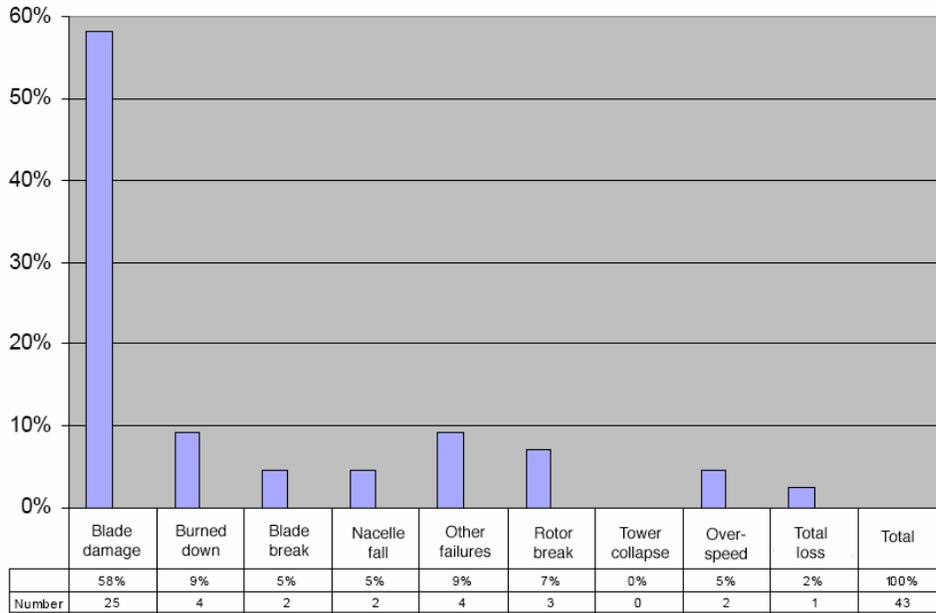
These 43 cases involve the time period from 1991 until July 2001.

## **3.2 Turbine Population**

The total number of operating years of all 1566 wind turbines included in the database at the end of July 2001 was about 13,000 years. The 43 serious damage incidents correspond to 0.33 critical incidents per 100 operation years.

## **3.3 Failures and Incidents**

The 43 cases of turbine damage from the WMEP database are arranged by type of damage. The results are presented in Figure 3.1.



**Fig. 3.1: Type of damage for 43 cases involving serious damage.**

Blade fracture, rotor failure, nacelle fall, and tower collapse are all of importance to risk analyses, because it is these phenomena that can cause damage to people or objects in the nearby surroundings. The other types of damage result only in economic damages.

With regards to blade fracture, there has been one report of a case where one blade broke off the turbine. For the second case, no information is given on the number of fractured blades. For further analysis, a conservative conclusion was made that all three blades had fractured. So, in total, there were four broken blades in the two cases of blade fracture.

Three cases of rotor failure were reported. With this type of failure there are a few possibilities:

1. The rotor failure causes the blades to break off and to be thrown from the turbine.
2. The rotor breaks off and falls from the turbine. The parts fall close to the turbine and the effects are similar to those of a fallen nacelle.

One case was reported that involved blades striking the tower, and then breaking off. As a result, the number of cases of blade fracture becomes seven. In the other two cases it was reported that damage was found, but not whether blades were broken or a rotor fell. For these two cases it is assumed that it was the rotor that fell. It should be noted that there is no mention of brake tips falling, or of small parts falling from the nacelle or hub.

The total number of critical turbine damage cases that are relevant to the risk analysis is shown in Table 3.1. The research done by ISET focused on critical cases, therefore there is no information on small parts. Nowhere is there mention of brake tip failure.

**Table 3.1: Number of critical turbine damage cases with the potential to cause danger to the surrounding area**

<b>Part</b>	<b>Number</b>	<b>Turbine Years</b>
Blade separation	7	13000
Fallen nacelle and/or rotor	4	13000
Tower failure	0	13000

### **3.4 Trends**

From the analysis conducted by ISET, the following trend develops. Lightning seemed to cause a great percentage (34%) of the heavy damage to turbine blades. However, as the blades include better lightning protection systems, the number of heavy damage cases decreases significantly. Now lightning causes only limited damage to the blade surface, near the receptors which during preventive maintenance can be repaired.

## 4. FAILURE FREQUENCIES

In Chapters 2 and Chapter 3 overviews are given for the total number of incidents per turbine part. The failure frequencies are calculated based on all reported incidents, from the EMD database as well as the ISET database. Table 4.1 gives an overview of the total number of incidents, and the number of turbine-years for which the incidents have relevance.

Table 4.1 also gives the calculated failure frequencies. The expected failure frequency value for each part is calculated by dividing the total number of incidents by the number of relevant turbine-years. It appears that the number of incidents is small compared to the number of turbine-years, so the calculated expected value has a non-negligible uncertainty that can be quantified by the probability density function of the expected value. The occurrence of a particular incident can be modeled with a Poisson process. In a Poisson process there is an invariable chance of an incident occurring in time. For  $n$  incidents in  $T$  turbine-years, the probability density function for the failure frequency per turbine-year,  $f(\lambda)$ , is given by the Gamma function [4], or

$$f(\lambda; \alpha, \beta) = \frac{\beta^{-\alpha} \lambda^{\alpha-1} \exp\left(-\frac{\lambda}{\beta}\right)}{\Gamma(\alpha)}$$

where

$$\alpha = n$$

$$\beta = 1/T$$

Next to the expected value in Table 4.1 is also listed the 95 % upper limit for the failure frequency.

**Table 4.1: Failure frequencies per part.**

Part	Total EMD and ISET		Failure Frequency [1/turbine-year]	
	Number	Turbine years	Expected Value	95% upper limit
Blades <sup>1)</sup>	27	42889	$6.3 \cdot 10^{-4}$	$8.4 \cdot 10^{-4}$
Tips	3	24006	$1.2 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$
Nacelle	8.5	42889	$2.0 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$
Tower	2.5	42889	$5.8 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$
Small Parts	21	17452	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$

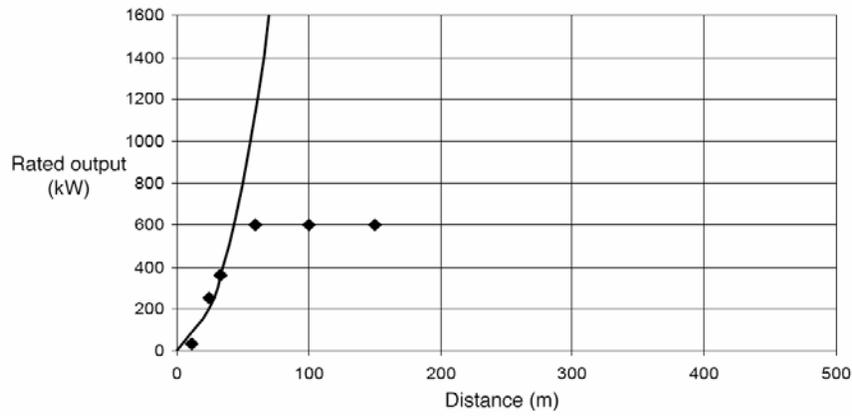
<sup>1)</sup> Failure frequency is based on total number of turbine-years, so this indicates the chance of blade failure per turbine per year.

## 5. ANALYSIS OF INCIDENTS AND THROW DISTANCES

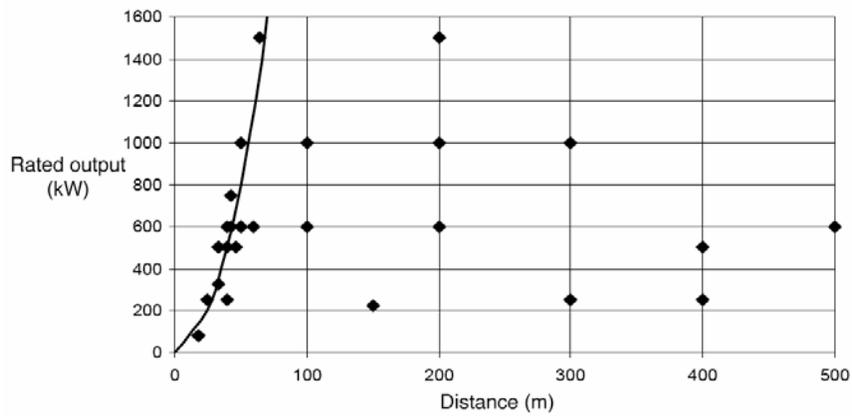
In addition to determining the failure frequencies of blades, tips, turbines, and small parts, attention was also paid to accident scenarios. To calculate the risk turbines pose to their surroundings, it is important to know what throw distances are probable and how large the separated parts are. Therefore, an analysis was done of incidents and accidents that are published in detail, for which the following sources are consulted:

- <http://wilfriedheck.tripod.com/unf.htm>
- <http://querulant.com/querulant/wind>
- <http://home.wxs.nl/%Ewindsnieuws.htm>
- <http://home.wxs.nl/~hzwarber/wind/feiten/veilig.htm>
- Energie- en Milieusp. 4-95
- Windnieuws ODE 94/1
- Windnieuws ODE 94/2
- Windnieuws ODE Febr. 95
- Windnieuws ODE April 95
- Windnieuws ODE Jan. 96
- Windnieuws ODE Juni 96
- Windnieuws ODE Sept. 96
- Duurzame Energie Dec. 95
- Duurzame Energie Febr. 95

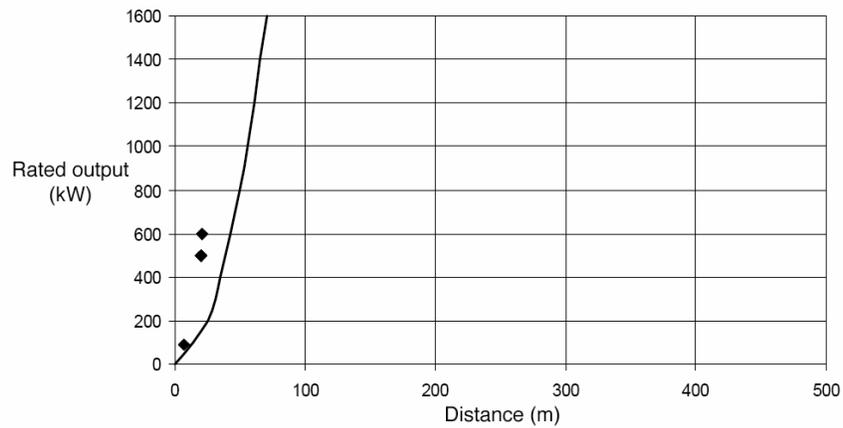
The results of the analyses are presented in Figures 5.1 through 5.4. In these figures, one for each type of incident, the reported throw distance is presented (x-axis) as a function of the rated power (y-axis). The curves in each graph relate the approximate rotor diameter associated with corresponding rated power level. The curves are added to put the throw distances in perspective.



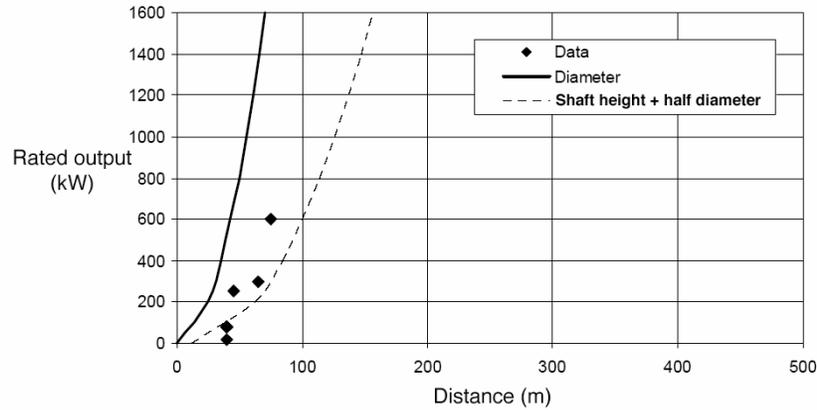
**Fig. 5.1:** Throw distance of entire blades as a function of the rated power output, the drawn line gives the rotor diameter.



**Fig. 5.2:** Throw distance of tips and small blade pieces as a function of the rated power output, the drawn line gives the rotor diameter.



**Fig. 5.3:** Throw distance due to fall of nacelles and rotors, as a function of the rated power output, the drawn line gives the rotor diameter.



**Fig. 5.4:** Throw distance due to tower collapse as a function of the rated power output, the drawn line gives the rotor diameter. The dotted line gives the shaft height plus rotor radius (half diameter).

The following can be concluded from Figures 5.1 through 5.4.

- Small blade parts and tips can fly very far. The maximum distance reported is 500 m.
- The maximum throw distance of an entire blade found during this analysis is about 150 m. Distances of 400 and 600 meters for entire blades were also reported in publications. Nevertheless, attempts to confirm these numbers through contacting the owner or the publisher were unsuccessful.
- When a rotor or nacelle falls down, the risk zone is approximately equal to half a rotor diameter.
- When an entire tower fails, the risk zone is equal to the height of the tower plus half a rotor diameter.

## 6. CONCLUSIONS

### 6.1 Recommended Risk Analysis Values

ECN has analyzed the reported incident information for a large population of wind turbines in Denmark and Germany and determined the frequencies of:

- Blade fracture;
- Tips and other small parts breaking off;
- Tower failure at the tower root;
- Rotor or nacelle falling down;
- Small parts falling from the rotor or nacelle.

The chance of blade fracture is further separated into:

- Failure at nominal operating rpm (revolutions per minute);
- Failure during mechanical braking;
- Failure due to overspeed.

The ECN also did an in-depth study of the possible throw distances due to turbine failure. The results of this analysis are summarized in Table 6.1.

**Table 6.1: Failure frequencies and maximum reported throw distances**

Part	Failure frequency per turbine per year			Maximum throw distance [m] (reported and confirmed)
	Expected Value	95% upper limit	Recommended Risk Analysis Value [1/yr]	
Entire blade	$6.3 \cdot 10^{-4}$	$8.4 \cdot 10^{-4}$	$8.4 \cdot 10^{-4}$	150
<i>Nominal rpm</i>			$4.2 \cdot 10^{-4}$	
<i>Mechanical braking</i>			$4.2 \cdot 10^{-4}$	
<i>Overspeed</i>			$5.0 \cdot 10^{-6}$	
Tip or piece of blade	$1.2 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	500
Tower	$5.8 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	Shaft height + half diameter
Nacelle and/or rotor	$2.0 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$	Half diameter
Small parts from nacelle	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	Half diameter

## 6.2 Closing Remarks

Until now ECN, NRG, and KEMA and other organizations have conducted various risk analyses. The failure frequencies used for these analyses were derived from a study of Danish failure frequencies like those published between 1990 and 1992 in WindStats with the expected values for the failure frequencies of blade fracture per turbine split up into:

- Failure at nominal operating rpm  $1.3 \cdot 10^{-3}$  per year
- Failure during mechanical braking (~1.25 times nominal rpm)  $1.3 \cdot 10^{-3}$  per year
- Failure by overspeed (~2 times nominal rpm)  $5.0 \cdot 10^{-6}$  per year

The total chance of blade fracture per turbine was  $2.6 \cdot 10^{-3}$  per year. The analysis of the new failure information shows that this chance is decreased by a factor of 3.1 to  $8.4 \cdot 10^{-4}$ . The recommended risk analysis value is 3.1 times smaller than the one used in the past.

Failure during overspeed is not reported in either ISET's or EMD's data. The ISET data did reveal that two incidents led to a long-lasting overspeed situation. The chance of this happening is therefore  $2/13,000 = 1.5 \cdot 10^{-4}$ . The blades stayed in one piece in these situations. Until now the chance of overspeed was determined by multiplying the chance of electric grid failure (5 times per year), the chance of failure of the first brake system ( $10^{-3}$  per claim), the

chance of failure of the second brake system ( $10^{-3}$  per claim), and the chance of blade fracture in this situation ( $=1$ ). Here it is recommended to retain the old calculation value for blade fracture during overspeed, as  $5.0 \cdot 10^{-6}$  per year.

Information about the tower failures was until now never derived from failure frequency databases. Until now the assumption was made that the chance of a tower failure had to be at least ten times smaller than that of a blade failure because it goes nearly unreported. The calculation value of  $1.0 \cdot 10^{-4}$  was used. The new calculation value based on the 95% upper limit is 1.3 times larger than the value that was used in the past.

## 7. REFERENCES

- [1] Data extract on severe accidents with wind turbines in Denmark, Energi- og Miljødata, March 2001.
- [2] M. Durstewitz , B. Hahn, M. Krallmann, Schwere Schäden an Windenergieanlagen und Ihre Auswirkungen, ISET, Kassel, November 2001.
- [3] Besluit Voorzieningen en Installaties Milieubeheer, Algemene Maatregel van Bestuur, Staatsblad 2001 487, 18 oktober 2001.
- [4] D. Vose, Risk Analysis; A Quantitative Guide, 2<sup>nd</sup> edition, John Wiley & Sons, June 2000.